Nuclear Waste Policy Act
(Section 113)

Site Characterization Progress Report:
Yucca Mountain, Nevada

April 1, 1996 - September 30, 1996

Number 15

April 1997

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

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Department of Energy

Washington, DC 20585

April 23, 1997

NOTE TO READERS:

During this reporting period, we released our revised Program Plan which outlines a focused, integrated program that will achieve key Program and statutory objectives. The plan identifies three near-term objectives: (1) updating in 1997 the regulatory framework for repository site characterization, (2) supporting a 1998 viability assessment, and (3) if the site is suitable, submitting a Secretarial site recommendation to the President in 2001 and a license application to the Nuclear Regulatory Commission in 2002. In support of the first near-term objective, we drafted a Notice of Proposed Rulemaking to amend the repository siting process. This notice was subsequently published in the *Federal Register* on December 16, 1996, which began a 60-day public comment period. Subsequent notices extended the comment period to May 16, 1997.

Tunneling was completed in the Exploratory Studies Facility main drift, and the tunnel boring machine continued tunneling up the south ramp. In December 1996, we encountered worse ground conditions than expected, but even with these poor ground conditions, the tunnel boring machine reached the south portal on April 25, 1997. The completion of the main drift marks a shift in emphasis from constructing the Exploratory Studies Facility to conducting scientific experiments in the tunnel and alcoves.

The initial construction phase of the Thermal Testing Facility was completed and the first phase of the in situ heater tests began on schedule in August 1996. This eighteen month test will measure thermal effects on the rock and the moisture within the rock.

Most of our site investigations and design and performance assessment activities this period were directed toward providing information for the 1998 viability assessment, our second near-term objective. Several studies and modeling activities were completed that provided new information on the potential percolation flux in the repository horizon. The new information indicated the potential for preferential water pathways and for a percolation flux higher than previously indicated.

During the next period, we will continue modeling, testing, and data collection activities to reduce the uncertainty in the range of percolation flux that can be expected in the repository horizon. In the Note to Readers for the 14th Progress Report, we indicated that we expected to issue the revised Waste Containment and Isolation Strategy during the first half of 1997. We will re-evaluate issuance of the strategy as a consequence of any changes to the predicted range of percolation flux rates. In addition, we will reassess the results from our on-going repository design and performance activities discussed in this progress report in light of these same changes.

Sincerely,

Lake H. Barrett, Acting Director
Office of Civilian Radioactive
Waste Management

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EXECUTIVE SUMMARY

During the second half of fiscal year 1996, activities at the Yucca Mountain Site Characterization Project (Project) supported the objectives of the revised Program Plan released this period by the Office of Civilian Radioactive Waste Management of the U.S. Department of Energy (Department). Outlined in the revised plan is a focused, integrated program of site characterization, design, engineering, environmental, and performance assessment activities that will achieve key Program and statutory objectives. The plan will result in the development of a license application for repository construction at Yucca Mountain, if the site is found suitable. The revised plan is designed to enable the Project to make measurable and significant progress toward key objectives within the financial resources that can be realistically expected.

Activities this period focused on two of the three near-term objectives of the revised plan: updating in 1997 the regulatory framework for determining the suitability of the site for the proposed repository concept and providing information for a 1998 viability assessment of continuing toward the licensing of a repository. In support of the first objective, the Department published a Notice of Proposed Rulemaking to amend the repository siting process. Site investigations and design and performance assessment activities, however, primarily were directed toward providing information for the 1998 viability assessment.

Particularly important information needed to understand the unsaturated zone came from several investigations and modeling activities completed this period. The information indicated that the percolation flux at the repository level might be greater than previously thought. Although the data are preliminary and will require confirmation, the effects on the current flow model for the unsaturated zone are being evaluated. This model will be a key component of the performance assessment that will be used to support the viability assessment.

Site characterization activities at Yucca Mountain, Nevada, from April 1, 1996, through September 30, 1996. Fifteenth in a series reported in accordance with the requirements of Section 113(b)(3) of the Nuclear Waste Policy Act of 1982, as amended, and 10 CFR 60.18(g).

Location of Yucca Mountain site.

The Project has also developed a new design approach that uses the advanced conceptual design published during the last reporting period as a base for developing a design that will support the viability assessment. This design will evolve over time and become more detailed as data and analyses are refined and design studies are completed. The evolving design will support the environmental impact statement, site recommendation, and license application.

In addition, construction in the Exploratory Studies Facility is nearing completion, opening up more of the underground tunnel and alcoves for testing and analysis to support the viability assessment. The excavation of the repository level main drift was completed on July 2, 1996, well ahead of schedule. The tunnel boring machine is now tunneling up the south ramp and is expected to reach the south portal early in 1997. The initial construction phase of the Thermal Testing Facility was completed and the first phase of the in situ heater tests began on schedule. In addition, phase-one construction was completed for the first of two alcoves that will provide access to the Ghost Dance fault.

The following sections discuss the revised Program Plan and report Project progress.

REVISED PROGRAM PLAN

Program Plan Objectives

Fiscal Year 1997

- *Regulatory framework update*

Fiscal Year 1998

- *Viability assessment*
 - *Design of critical elements of repository concept and waste package*
 - *Total system performance assessment*
 - *Plan and cost to complete license application*
 - *Cost to construct and operate repository*

Fiscal Year 2001

- *Secretarial site recommendation*

Fiscal Year 2002

- *License application*

The Department released draft Revision 1 of its Program Plan in June. The Plan identifies three near-term objectives: (1) updating in 1997 the regulatory framework for repository siting to be consistent with a more focused performance-driven program; (2) supporting an assessment by 1998 of the viability of continuing with actions leading to the licensing of a repository; and (3) if the site is suitable, submitting a Secretarial site recommendation to the President in 2001, and a license application to the U.S. Nuclear Regulatory Commission (Commission) in 2002.

To achieve the first objective, the Department decided to streamline its siting guidelines (10 CFR Part 960) to respond to policy changes and increased technical understanding of the Yucca Mountain site. In 1987, legislation required the Department to characterize a single site instead of multiple sites, and in 1992, directed the U.S. Environmental Protection Agency (EPA) to develop site-specific radiation standards to protect the public. The Department proposed, through the public rulemaking process,

amendments to its siting guidelines to add a site-specific subpart focused on the overall preclosure and postclosure performance of a potential repository system at Yucca Mountain. This process began during this reporting period with the drafting of a Notice of Proposed Rulemaking that was published for public comment in the *Federal Register* on December 16, 1996. The Department intends to publish the final rule in 1997.

The Department also continued to follow progress by the EPA on the rulemaking activities on a new public health and safety standard for protection from radiation releases applicable to Yucca Mountain. The Department's primary focus in site characterization, as well as design, operation, and closure of any repository, is on the protection of the health and safety of the public and preservation of the environment. The Department believes that the final standard is critical to the future of geologic disposal in this country and considers three issues most important to the ability to implement the standard in the licensing environment. These issues are the length of the regulatory time period, the dose limits for individuals and ground-water protection, and the location and characteristics of the critical population group.

The second main objective of the Program Plan is to address by 1998 the open technical issues, including those related to the waste containment and isolation strategy, so that an informed assessment can be made of the viability of licensing and constructing a geologic repository at the Yucca Mountain site. This viability assessment represents a logical convergence point at which the Department can provide the basis for a measurably improved appraisal of the prospects for geologic disposal at the Yucca Mountain site. The deliverables that contribute to this assessment include the following:

- A package of more specific design work on the critical elements of the repository and the waste package, including a concept of operations that identifies available technologies to accomplish the objectives of geologic disposal

The revised Program Plan provides a focused, integrated program toward repository operation.

-
-
- A total system performance assessment, based upon this design concept and available data, that will describe the probable behavior of the repository system
 - A plan and cost estimate for the remaining work required to complete a license application
 - An estimate of the cost to construct and operate the repository.

After the viability assessment, if the site is determined to be viable, the Department will prepare the additional information required for the Secretary of Energy's site recommendation to the President and for the license application. As part of the site recommendation and license application process, the draft repository environmental impact statement will be issued for public review and comment in 1999 and the final repository environmental impact statement will be issued in 2000.

If the site is found suitable in accordance with the siting guidelines, the Department will implement the third main objective of the Program Plan. The Secretary will issue a site recommendation in 2001 following public hearings to be held in the State of Nevada. If the site is approved by the President and Congress, a license application will be submitted to the Commission in 2002 requesting authorization to construct a repository. This schedule will allow repository operations to emplace waste beginning in 2010.

***Primary Objectives of the
Waste Containment and
Isolation Strategy***

- *Acceptably low annual doses to a member of the public living near the site*
- *Containment of radionuclides within waste packages for several thousand years*

To help direct the remaining work needed to support Program Plan objectives, the Department continued to refine its strategy for evaluating the ability of the site to contain and isolate waste. This strategy has made it possible to further focus and narrow the remaining work scope needed to support the viability assessment, the evaluation of site suitability, and the preparation of a license application for submittal to the Commission. The refined waste containment and isolation strategy under development reflects the acquired knowledge of the site and its natural barriers, as well as the likely influence of site conditions on the performance of potential engineered barriers. The strategy focuses on two technical objectives: first, to limit the annual dose to members of the general public following permanent closure of the repository; and second, to contain the radionuclides within the emplaced waste packages for several thousand years during the period of highest radionuclide inventory and temperature.

The strategy suggests a focused hypothesis testing and analysis program that would resolve questions about a number of open technical issues. These issues primarily address movement of water through Yucca Mountain, selection of materials for the waste package, and the need for and feasibility of using additional engineered barriers, such as backfill, to enhance overall repository performance. Specifically, the system attributes recognized to be most important for predicting performance of engineered and natural barriers are rate of water seepage into the repository, waste package lifetime (containment), rate of release of radionuclides from breached waste packages, radionuclide transport through engineered and natural barriers, and dilution in the saturated zone below the repository. A summary version of the strategy was provided to the Nuclear Waste Technical Review Board and to the Commission in July 1996. A detailed version, providing the technical bases for the strategy, will be completed late in fiscal year 1997. The strategy is currently being re-evaluated as the Project's understanding of site characteristics, such as percolation flux, evolves.

***Attributes Most Important
for Predicting Performance
of Engineered and Natural
Barriers***

- *Rate of water seepage into the repository*
- *Waste package lifetime (containment)*
- *Rate of release of radionuclides from breached waste packages*
- *Radionuclide transport through engineered and natural barriers, including dilution in the saturated zone below the repository.*

As the Project has evolved to meet changes in regulatory policies and respond to increasing technical understanding of the site, changes in the testing and analysis program for site characterization have necessarily occurred. Recognizing this, the Department has begun an effort to document these changes and provide traceability to the program outlined in the Site Characterization Plan issued in 1988. Summary information is included as Appendix A to this progress report.

The Department has begun documenting how the Program has changed since the Site Characterization Plan was issued.

Specific progress in site investigations, design, and performance assessment supporting the revised Program Plan is discussed in the following section on Project progress.

PROJECT PROGRESS

Project activities this reporting period supported the objectives of the revised Program Plan. The following sections report progress in Project programmatic activities, site investigations, repository design, waste package, performance assessment, and Exploratory Studies Facility design and construction. Specific details relating to Project activities are presented in the respective chapters of the report and in supporting technical papers and reports referenced throughout the main body of the report.

Programmatic Activities

To support implementing the revised Program Plan, the Yucca Mountain Site Characterization Office refocused project planning and licensing activities to ensure efficient, measurable progress toward providing information to allow a viability assessment of Yucca Mountain as a permanent geologic repository.

The Department's long-range plan covers activities planned for next fiscal year through the submission of the license application in 2002.

Planning. The Project revised its long-range plan to reflect new Program Plan goals and objectives and then developed its detailed annual planning for fiscal year 1997. The long-range plan compiles the assumptions, work scopes, schedules, milestones, deliverables, cost estimates, and risks associated with implementing the revised draft Program Plan through the submission of the license application in 2002. As a part of the plan, the Project developed an Integrated Project Schedule, which is used to identify a set of activities necessary to develop a credible viability assessment, environmental impact statement, site recommendation, and license application. The Integrated Project Schedule also analyzes critical paths and helps determine the impacts of funding constraints.

A revised preclosure tectonics design approach will identify and design for two categories of design basis events, consistent with the proposed requirements in the proposed rulemaking for 10 CFR Part 60.

Regulatory Activities. The Department and the Commission focused on reaching agreement on the methodologies that will be used to address issues of seismic hazards and criticality. During this period, the Commission stated that sufficient information exists to close all comments on the first seismic topical report, which describes the probabilistic seismic hazard assessment methodology for the potential repository. The Project plans to revise the report in accordance with Commission staff comments and reissue it early in fiscal year 1997. In response to Commission staff comments, the Department revised its second seismic topical report, which describes the seismic design methodology for systems, structures, and components at Yucca Mountain. The Department decided to adopt an approach to preclosure seismic design that incorporates the requirement to identify and design for two categories of design basis events. The categories are determined on the basis of the likelihood of occurrence and importance to radiological safety. This approach is consistent with the proposed requirements in the Commission's proposed rulemaking for 10 CFR Part 60.

The Department completed the Disposal Criticality Analysis Methodology Technical Report. This report provides a preliminary description of the proposed risk-based disposal criticality analysis methodology and will be used to develop the topical report on the same subject. The topical report, planned for submittal to the Commission in 1998, will seek Commission acceptance of the proposed methodology that will include the technical basis for burnup credit.

The Department completed a preliminary description of the proposed risk-based disposal criticality analysis methodology.

Quality Assurance. In quality assurance activities, work continued to revise procedures to fully implement Revision 5 of the Quality Assurance Requirements and Description document, the principal Program quality assurance requirements document. Results of audits and surveillances indicated that the Office of Civilian Radioactive Waste Management Quality Assurance Program was in compliance with requirements, effectively implemented, and satisfactory overall.

In September 1996, the Department responded to the review by the Commission staff of its report tracing a sample of flowdown of 10 CFR Part 60 requirements to the Exploratory Studies Facility design. The response addressed two groups of Commission comments: those where the Department's interpretation of the requirements differs from that of the Commission and those where the Department's interpretation or application has changed since it issued the original report. The Department also explained that design packages were no longer used for the Exploratory Studies Facility; instead, individual parts, such as the south portal, are released. Thus, the commitment to reissue the Regulatory Compliance Review Report for each major design package is no longer appropriate. Instead, the Department thinks the already revised Exploratory Studies Facility Design Requirements document, which clearly shows how 10 CFR Part 60 requirements are addressed, meets the commitment to update the Regulatory Compliance Review Report. The Department's response also indicated that it believes it has adequately addressed the recommendations from the in-field verification held in April 1995.

Program Outreach. In Program outreach activities, the Project completed a video to inform the public and Project stakeholders about the scientific studies at Yucca Mountain

Community members interact with Project scientists in neighborhood dialogues.

since the beginning of the year. The Project staff also compiled a video entitled "Geologic Disposal of Nuclear Waste: Solving an Environmental Problem." The video depicts various aspects of the nuclear waste program and is suitable for general audiences.

Numerous educational activities continued, including operation of the Yucca Mountain Science Centers, Discovery Days, workshops, neighborhood dialogues, and the JASON Project. A neighborhood dialogue was held in West Las Vegas, where members of the community met with Project staff to ask questions. Project staff also helped develop exhibits for the International High-Level Radioactive Waste Conference held April 29-May 3, 1996, in Las Vegas, Nevada. Tours were provided for guests from the conference.

Site Investigations and Analyses

As construction of the Exploratory Studies Facility ends, testing and analysis to support the objectives of the revised draft Program Plan are being emphasized.

Site investigations and analyses this period supported the development of the viability assessment. Work supporting the assessment consists of a set of tasks that address the major unresolved technical questions about the design of the repository and its expected performance in the geologic setting. The technical questions include thermal effects, hydrologic properties of major faults, percolation flux, and implications of climate change for repository performance. As construction of the Exploratory Studies Facility ends, emphasis has shifted toward testing and analysis to answer these questions and to support the objectives of the revised draft Program Plan, particularly the 1998 viability assessment.

Ground-Water Flow. One of the highest priorities of the Project continues to be determining the amount of percolation flux in the repository horizon. Percolation flux is the rate at which water slowly flows through the cracks and pores of the rock. Recent modeling and design activities have assumed flux rates in the 0.1 millimeter per year range. Indeed, much of the information gathered thus far through site investigation supports the hypothesis that over-all flux rates are low. To date, during excavation in the Exploratory Studies Facility through the main drift, no natural water has been found dripping or flowing into the excavation. Some of the dryness, however, may be attributable to the effects of construction ventilation. Interpretations of isotopic data from pore waters and fracture coatings in the Exploratory Studies Facility have been consistent with the hypothesis that only limited quantities

of water have moved through the excavated area during the last 100,000 years. Still, the uncertainty in the actual range of percolation fluxes remains one of the key questions surrounding the natural system. Information on percolation flux is critical to determining seepage into the repository drifts and to performance assessments that will calculate postclosure performance.

During the reporting period, several studies and modeling activities were completed that provided new information on the potential percolation flux. This new information indicated the potential for preferential water pathways and for a percolation flux at the repository horizon that may be higher than previously indicated. In light of the new and evolving evidence, the Project is re-evaluating its conceptual model of unsaturated zone flow. The following discussion outlines some of the new information acquired this reporting period.

The Project is re-evaluating the conceptual model of unsaturated zone flow in light of new information.

Information on potential pathways was provided by systematic and feature sampling in the Exploratory Studies Facility. Sampling results indicated that chlorine-36 from weapons testing occurs in some samples from fractured or faulted zones, indicating that at least a small part of the water at these locations is less than 50 years old. Locations with multiple samples that have indications of chlorine-36 from weapons testing appear to be associated with the Bow Ridge fault, the Drill Hole Wash fault, and the Sundance fault. Other locations are associated with features such as cooling joints or breccia zones. Technetium-99 from weapons testing has been detected in the Bow Ridge fault exposed in the Exploratory Studies Facility, corroborating the presence of chlorine-36 from weapons testing found in that area.

A major infiltration study was completed during this reporting period that indicates that infiltration rates are higher than previously thought. In the first part of the study, a multiple linear regression model was used to relate subsurface moisture changes in 69 neutron holes to annual precipitation, depth to bedrock, geomorphic position, and other hydrogeologic factors. Results indicated that the average shallow infiltration over a 230-square-kilometer area around Yucca Mountain was 11.6 millimeters per year for the period 1984 to 1995.

Infiltration rates may be higher than previously thought, and the higher rates could directly affect the flux at the repository horizon.

In the second part of the study, shallow infiltration estimates were used to derive a numerical, deterministic model of net infiltration that averages 4.5 millimeters per year over the Yucca Mountain area for an average precipitation year. A similar model based on the locations of the 69 neutron holes produced an estimated average net infiltration of 5.5 millimeters per year. Simulation of a possible future climate with double the current average annual precipitation resulted in an increase of net infiltration by a factor of five to seven. The higher infiltration rates could directly affect the percolation flux at the repository horizon.

Because no direct measurement exists, percolation flux must be determined using a combination of indirect methods involving field testing and modeling at different scales.

Because no direct measurements exist, the determination of percolation flux depends on a combination of indirect methods involving field testing and modeling at different scales. Analysis of available temperature and heat flow data indicate that the average percolation flux in the repository area may be about 5 millimeters per year. This flux is considerably larger than previous estimates that indicated a low flux in the area of 0.1 millimeters per year. Although the data for this new higher flux are limited and the method needs to be verified for this type of analysis, a higher flux has potentially significant implications for repository performance, potentially affecting lateral flow in the Paintbrush nonwelded hydrogeologic unit and the ability to maintain a dry repository.

Three-dimensional analysis of lateral flow using the unsaturated zone model indicates that lateral flow within the Paintbrush nonwelded hydrogeologic unit is most prevalent at low percolation flux rates. When percolation flux rates are higher (about 5 millimeters per year), however, the model indicates there may be little lateral flow. Thus, the effectiveness of the Paintbrush nonwelded hydrogeologic unit in diverting water from the repository horizon could be reduced. Also, simulations using an average net infiltration rate of 4.4 millimeters per year indicate lateral flow within and around the Paintbrush nonwelded unit is small. This rate of 4.4 millimeters per year differs from that estimated in the infiltration study, because the calculations used the potential repository area rather than the larger study area around Yucca Mountain.

If net infiltration rates are in the range of 4.4 millimeters per year, the heat from the emplaced waste may not be able to drive water in the host rock away from the repository.

Percolation rates also affect the ability of the heat from the waste to drive the water in the host rock away and to produce and maintain a dry repository. Complete dryout may occur with low net infiltration rates (0.1 millimeters per year) but is not likely to occur with higher net infiltration rates (4.4 millimeters per year).

The result implies that only partial dryout is likely and the time that low relative humidity conditions prevail in the emplacement drifts may be reduced.

Lateral flow above the low permeability zeolitic rocks within the Calico Hills and the Prow Pass units (below the potential repository horizon) is seen in most of the two-dimensional and three-dimensional simulations. In addition, analysis of the temperature gradient performed suggests more vertical percolation flux within the Topopah Spring Tuff layers than in the underlying Calico Hills and Prow Pass layers, thereby indicating lateral flow must occur above these layers. Lateral flow is a key issue for determining how much dependence to place on retardation and sorption as a component of flow through the zeolitic rocks.

Modeling and temperature data indicate lateral flow occurs above the Calico Hills and Prow Pass units.

To help answer remaining and emerging questions about the unsaturated zone and the hydrogeologic system of Yucca Mountain, the Project continued to refine its modeling tools and has begun to conduct thermal tests of the effects of heat on the surrounding rocks. Considerable progress was made in developing the three-dimensional site-scale model of the unsaturated zone. A revised numerical grid that uses about 30 computational layers has increased the geologic realism and accuracy in the representation. The model now represents important processes and components of Yucca Mountain, including faults and fault offsets, perched water in appropriate locations, rock matrix and fracture properties, observed temperature profiles, and fast flow paths. Calibration and sensitivity studies are continuing. This model is a major tool in the conceptualization of the hydrogeologic system at Yucca Mountain.

The three-dimensional site-scale model of the unsaturated zone now represents important processes and components of Yucca Mountain.

Single-element heater testing began in the Thermal Testing Facility on schedule in August 1996. In the test, the heat comes from electric heaters that simulate the heat from emplaced waste in a repository. Preliminary data indicate that the sensors are operating properly. This eighteen-month test will measure the thermal effects on rock and moisture within the rock and will provide an opportunity to test the instruments before the larger and more complex drift-scale test is conducted. Preliminary results from the single-element heater test are expected in the second half of fiscal year 1997.

For the single-element heater test, the heater element is installed in a borehole surrounded by instruments. The heater is 5 meters long, outputs about 4 kilowatts, and will heat the surrounding rock to about 200°C.

Next period, the Project will continue its modeling, testing, and data collection activities to reduce the uncertainty in the range of percolation flux that can be expected in the repository horizon. The Project also will examine all available data and analysis related to percolation flux to determine needed changes in the percolation flux model and in the waste containment and isolation strategy. In addition, results from ongoing repository design and performance assessment activities reported in this progress report will be reassessed in light of the potentially higher flux rates.

Aqueous Transport. The Project continued to expand its understanding of the dispersion and depletion of radionuclides in the natural system. Performance assessments show that the rate at which radionuclides are mobilized from the waste form is a key factor in determining annual peak doses.

Sorption studies have identified parameters that control radionuclide sorption.

Studies related to sorption indicate that under ambient conditions, clinoptilolite beneath the repository horizon is unlikely to be transformed to analcime within 10,000 years. Thus, the mineral is expected to provide sorptive capacity to retard radionuclides that may be released from the repository. Batch sorption studies indicated that neptunium (IV) may be significantly retarded under fracture flow conditions because of the calcite that commonly coats fractures.

Other sorption studies indicate that the reduction-oxidation potential is the most critical ground-water parameter for determining plutonium behavior in the flow system. Uranium sorption appears to be controlled by pH, alkalinity, and alkaline earth ion concentrations. The carbonate content of rocks and the presence of ferrous iron on tuff surfaces appear to affect the sorption of neptunium. Studies are continuing to determine the effects of these parameters on sorption.

Data on solubility limits show that uranium, thorium, neptunium, plutonium, and americium have low solubilities in Yucca Mountain waters. Because of the relatively low concentration of colloids in well water from UE-25 J#13, the sorption of radionuclides to individual colloids would probably have to be extremely high to carry a significant amount of radionuclides from the repository to the accessible environment. Comparisons of the predicted uptake of sorbing radionuclides by the tuff with actual data indicate that predicting diffusion using the batch sorption coefficient should result in conservative estimates.

Data from recent experiments indicate (a) diffusion from fractures into the matrix of the rock can take place even at relatively fast flow rates; (b) neptunium can be significantly retarded, even during a fracture-flow scenario, because of both diffusion into the matrix and sorption onto the minerals lining the fracture walls; and (c) fracture flow does not always result in fast pathways for actinide migration along fractures. Hence, calculations that incorporate simple fast-pathway assumptions may lead to unnecessarily conservative predictions of radionuclide releases to the accessible environment.

Using simple fast-pathway assumptions may lead to unnecessarily conservative predictions of radionuclide releases to the accessible environment.

Gaseous Transport. Data from pneumatic testing completed this period, have shown that there is significant interconnection of fractures within the welded intervals of the Tiva Canyon and the Topopah Spring hydrogeologic units. Pneumatic-pressure records indicate that pressure signals are transmitted nearly instantaneously throughout the entire Topopah Spring section, indicating that the fractures within the Topopah Spring Tuff are very permeable and highly interconnected within both the lithophysal and nonlithophysal subunits. Likewise, shut-in pressure monitoring of a borehole in the Bow Ridge Fault Alcove indicated that the Tiva Canyon welded hydrogeologic unit is highly permeable. Unusually young gas samples (80 to 90 percent modern carbon) have been collected from the lower Topopah Spring welded and the upper Calico Hills nonwelded hydrogeologic units. The samples were collected from borehole USW SD-12, which is located about 200 meters north of the Southern Ghost Dance Fault Alcove. In addition, changes in the barometric signals at these sampling stations suggests that the Ghost Dance fault influences gas movement.

Geology. Studies continue to understand the geology of the Yucca Mountain area and its effects on a potential repository. A probabilistic volcanic hazard analysis, completed this period, indicates that the aggregate expected annual frequency of a volcanic event intersecting the proposed repository is about 1.5×10^{-8} . Thus, there is little chance of potentially disruptive igneous activity at Yucca Mountain in 10,000 years. The major uncertainty in these calculations is the uncertainty in estimating the rate of volcanic events from small data sets and from modeling the spatial distribution of future events.

A probabilistic volcanic hazard analysis indicates there is little chance of disruptive igneous activity at Yucca Mountain in the next 10,000 years.

Geophysical data gathered this period corroborate map locations and extensiveness of faults in the Yucca Mountain area.

These data also corroborate the idea that the nature of the Paleozoic-Tertiary contact beneath Crater Flat and Yucca Mountain is not an active shallow detachment surface. Data indicate the contact is probably a depositional unconformity.

In the near term, site investigations information is used as input in developing geotechnical synthesis reports and as input to design and performance assessment evaluations and validation studies. These reports and evaluations will provide input for the viability assessment in 1998.

To that end, several major synthesis reports have been completed that will provide data for (a) design work on key elements of the repository and waste package, (b) the development, refinement, and validation of process models, and (c) the development of total system performance assessment models. The synthesis reports completed are for mineralogy and petrology studies, climate studies, unsaturated zone hydrology, unsaturated zone matrix hydrologic properties, gaseous-phase circulation in the unsaturated zone, preclosure tectonics, and characteristics of fractures (for the postclosure rock characteristics program).

Repository Design Activities

The design effort has shifted toward support of the 1998 viability assessment. Repository design activities this period included revising the design approach, establishing regulatory compliance criteria, determining efficiencies in emplacement layout and concept of operations, and performing thermal loading studies.

Design. This reporting period, the Project developed a design approach that uses the advanced conceptual design as a base for the ongoing development of a design that will support the viability assessment, environmental impact statement, site recommendation, and license application. Intended to be developed over the next five years, the design will provide adequate design information for licensing; detailed design for construction will be developed later. This so-called one-pass design approach would design various systems, structures, and components in an orderly manner and prioritize them to support the major Program objectives of viability assessment, environmental impact statement, site recommendation, and license application. The first phase of design will support the viability assessment and will emphasize key technical questions that affect waste containment and isolation,

system performance, and cost. The updated total system performance assessment for the viability assessment will use this first phase design.

At the same time as the viability assessment design effort is being developed, the Project will establish regulatory compliance criteria for important systems, structures, and components. These systems, structures, and components will then be prioritized into categories to identify the level of detail required for license submittal. Category 1 includes systems, structures, and components with no radiological importance. This category currently includes underground lighting and compressed air systems. Category 2 includes systems, structures, and components with radiological importance that have an existing regulatory precedent, while Category 3 includes those with radiological importance that have no regulatory precedent. Currently, Category 2 includes items such as electrical distribution and muck handling systems, and Category 3 includes items such as underground ventilation and ground support systems.

Design work to support the viability assessment will focus primarily on Category 3 elements and on systems, structures, and components impacted by key technical issues important to the assessment. The next design phase will support the preclosure radiological analysis and in turn support the license application. In addition, Category 3 and some Category 2 elements will be designed. Designing Category 3 elements first allows more time to address likely issues associated with first-of-a-kind aspects of repository design. In the final design phase, the remaining Category 2 elements and Category 1 elements will be designed.

Supporting Activities. Activities supporting design centered on revising, refining, and improving concepts developed during advanced conceptual design. The repository layout was revised to make better use of the available emplacement area. A change in the central exhaust drift position and eliminating a drift no longer needed for tunnel boring machine operation added about 100 acres

Categories Determining Level of Design Detail for License Application

1. *No radiological importance*
2. *Radiological importance; regulatory precedent*
3. *Radiological importance; no regulatory precedent*

Under improved repository layouts, the lower emplacement block east of the Ghost Dance fault may not have to be used.

of potentially usable emplacement area. This additional area would eliminate the need for the proposed lower emplacement block east of the Ghost Dance fault. In addition, the emplacement operations concept was revised so that waste packages would not be emplaced on railcars. This revision would eliminate the need to purchase and emplace over 10,000 railcars, thus reducing repository costs.

An engineered barrier concept study was conducted to assess whether performance enhancement in the engineered barrier system would be needed. The study indicated that neither backfill nor other performance enhancements were likely to be needed to meet repository performance objectives. The need for backfill could change, however, because of changes in performance objectives or because of design changes or evolving understanding of the site, particularly related to percolation flux. Therefore, the study recommended that the design should continue to provide the flexibility to incorporate a backfill emplacement system.

A thermal loading study recommended a temperature limit to protect the zeolite layer.

Other refinements resulted from a thermal loading study that re-examined several previously established thermal goals. The study recommended a temperature limit of 90°C for the average top of the zeolitic layer to protect this layer from dehydration and mineralogic changes that could affect its sorptive qualities. This zeolitic layer may play an important role in retarding the flow of radionuclides from degraded waste packages to the water table. The study also concluded that, given the assumptions at the time of the study, the planned thermal loading associated with the emplacement of 83 metric tons of uranium per acre would likely support meeting repository performance objectives for 10,000 years. Because of remaining uncertainties, however, the study recommended that at least one lower alternative thermal loading be retained. A lower thermal loading, however, would be more costly than the planned thermal loading and thus would only be pursued if future evaluations indicate the need.

A preliminary hazards analysis was developed as a step toward determining design basis events.

In other activities, a preliminary hazards analysis was developed as a step in determining design basis events. The Commission's proposed revision to 10 CFR Part 60 introduces the term "design basis events" and defines two categories on the basis of their importance to radiological safety and likelihood of occurrence. Category 1 design basis events are those natural and human-induced events that are reasonably likely to occur at least once before repository closure. Category 2 design basis events are other natural and human-induced events considered unlikely but

sufficiently credible to warrant consideration, taking into account the potential for significant radiological impacts on public health and safety. Analysis of design basis events will help determine the list of repository and waste package systems, structures, and components subject to quality assurance requirements.

Waste Package Design Activities

The waste package design continues to evolve as systems strategies and long-term performance strategies evolve. Design is now focused on the following four basic types of disposal containers, all of which are robust, multibarrier, metallic designs: (1) disposal container for 21 uncanistered pressurized water reactor fuel assemblies or 44 uncanistered boiling water reactor fuel assemblies, (2) disposal container for canistered fuel, (3) disposal canister for defense high-level waste glass canisters, and (4) type 3 modified to also accommodate DOE-owned spent nuclear fuel.

The container for high-level waste and DOE-owned spent nuclear fuel that is presently being considered would hold five canisters containing high-level waste glass with the gap in the center designed to hold DOE-owned spent nuclear fuel. A circular tube would be placed in the center of the disposal container and inside the tube would be a basket that would form nine square cells, each of which would hold a spent nuclear fuel assembly.

One disposal container design for defense high-level glass has been modified to accommodate DOE-owned spent nuclear fuel.

The Project understanding of technologies used to produce disposal containers advanced considerably. One promising method would fabricate the corrosion allowance (outer) barrier and the corrosion resistant (inner) barrier separately and then shrink fit the layers together. This method promises to be less expensive than producing an inner containment barrier as a welded cladding. More data, however, are needed on whether this method could provide sufficient electrical coupling between the layers so that the outer layer could provide galvanic protection for the inner layer.

An analysis of materials was completed for all major waste package components, including inner and outer barriers. Because of this analysis, Alloy 625, a nickel-chromium-molybdenum alloy, is considered the leading candidate for the corrosion resistant barrier

Preliminary analysis indicates there is little probability of a criticality occurring external to the waste package.

material and ASTM A 516 (carbon steel) is the leading candidate for the corrosion allowance barrier for both spent nuclear fuel and high-level waste glass disposal containers. Alloy 625 is one of the most weldable nickel-chromium-molybdenum alloys, making it very suitable for fabrication.

Criticality analyses were extended to consider events external to the waste package. Preliminary analyses indicate that the probability of such an event would be extremely small and that its potential impact on repository performance, if it were to occur, would be negligible.

Performance Assessment Program

Current efforts are focused on preparing for the next total system performance assessment to support the viability assessment. In addition, ground-water travel time calculations are being used to evaluate evolving site information regarding the amount of water percolation expected in the repository horizon. Total system performance assessment efforts revolved around planning, performing sensitivity analyses, and prioritizing of needed model development and site and design information.

Performance allocation analyses were performed to illustrate the importance of several key hypotheses of the waste containment and isolation strategy. The key hypotheses analyzed address various aspects of ground-water flow in the unsaturated zone, thermal effects of the emplaced waste, waste package degradation, and radionuclide transport in the saturated zone. The results stress the importance of and need for reducing uncertainties in unsaturated zone percolation rates, waste package corrosion, and radionuclide dilution in the saturated zone. The results were used to prioritize the development and testing of process models and site and design activities needed to support the viability assessment. Sensitivity analyses of process models evaluated the relative importance of input parameters, including uncertainties. In addition, a plan was completed outlining the performance assessment work required for the viability assessment, including technical tasks, responsibilities, and schedules.

Ground-Water Modeling. Numerical ground-water modeling studies that evaluated different modeling assumptions provided information about the relative importance of model parameters and physical processes. These studies indicated that the

spatial heterogeneity of flow and transport processes is important (including the location and spatial density of high permeability features or fracture network); thus the assumption of homogeneous rock properties is not adequate. Study results indicated that transient infiltration pulses need to be included in the calculations to correctly simulate fast flow paths. Fracture-matrix interactions were determined to be critical to ground-water flow through the mountain and must be incorporated into the mathematical models. For low surface-water infiltration rates ranging from 0.1 to 0.3 millimeters per year, the studies indicate that thin layers within the Paintbrush nonwelded hydrogeologic unit could divert much of the vertical percolation laterally and thus influence the flux at the potential repository horizon. For higher surface-water infiltration rates between 4.4 and 10 millimeters per year, however, the studies show that most of the vertical percolation would continue downward to the potential repository horizon.

In other ground-water modeling activities, a three-dimensional site-scale model of the unsaturated zone was developed to simulate the thermohydrologic response of the geologic system to heat generated by the emplaced waste. This model provides the first set of coupled heat and fluid flow calculations at the site scale that are fully three dimensional.

Modeling of unsaturated flow for a thermal load of 83 kilowatts per acre and surface infiltration rates of 0.1 and 0.3 millimeters per year indicates that the potential repository horizon would dry out starting at about 100 to 500 years and lasting until about 2000 to several thousands of years after repository closure. Modeling results for a surface infiltration of 4.4 and 10 millimeters per year indicate that the potential repository horizon would not dry out at any time because the heat generated by the emplaced waste would no longer be sufficient to vaporize the percolating water.

Performance of both the natural and the engineered barriers will depend heavily on the amount of percolation flux. Thus, reducing the uncertainty in the applicable range of percolation fluxes remains one of the highest priorities of the Project so that postclosure performance can be more accurately assessed.

Saturated zone model results indicate that there would be a significant increase in temperature at the water table beneath the potential repository. These results imply that a heat exchange

A model was developed that provides the first set of coupled heat and fluid flow calculations at the site scale that are fully three dimensional.

Modeling of unsaturated flow indicates that a percolation rate of 4.4 millimeters per year and higher will prevent the potential repository horizon from drying out.

Reducing the uncertainty in the amount of percolation flux remains one of the highest priorities of the Project.

A quality assurance readiness review and safety and design reviews were completed for the long-term corrosion test facility and testing began.

boundary condition at the water table should be incorporated into the unsaturated zone modeling. The results also suggest the possibility that waste heat would cause geochemical and mineralogic alterations in the saturated zone.

Engineered Barrier System Materials. Several material tests were conducted related to corrosion of waste package container materials. In addition, a formal quality assurance readiness review and safety and design reviews were completed for the long-term corrosion test facility. Testing began in the first of 12 test vessels just before the close of the reporting period. Conditions that increase the susceptibility of metals to aqueous film corrosion were investigated. Key parameters included surface contamination (salts) and surface condition of the metal. Results from humid air tests showed that corrosion rates were substantially increased when surfaces were etched chemically or coated with salt. Electrochemical tests indicated that nickel-based and titanium-based alloys exhibited the highest corrosion resistance. Other studies investigated how microbes present in Yucca Mountain might affect corrosion. Preliminary corrosion results with carbon steel specimens indicate that corrosion is enhanced more if three classes of bacteria are present together than if only a single class of organism is present. Preliminary modeling indicates that low-temperature oxidation would not significantly degrade the performance of thick corrosion-allowance materials for hundreds to thousands of years. This work is focusing initially on carbon steel as the principal candidate for the outer disposal container.

A study of chemical additives to backfill concluded that adding lime to control pH or iron to control Eh (reduction-oxidation potential) would not be effective in modifying the near-field geochemical environment for the time periods that would be needed. In addition, in concert with current design efforts, Alloy 625, a nickel-chromium-molybdenum alloy, was added to the corrosion testing program. Among nickel-chromium-molybdenum alloys, the corrosion resistance of this alloy in very aggressive environments is expected to be intermediate.

Performance Confirmation. A performance confirmation concept study was completed. The study report identifies the processes to be simulated for postclosure performance assessment in support of the license application and lists the site and design parameters needed for the analyses. The report also develops criteria for selecting the parameters that would require performance

confirmation and recommends parameters for which data will be needed to confirm the assumptions of the license application. The information and recommendations will be considered in the repository and waste package design.

Exploratory Studies Facility Design and Construction

Activities associated with the Exploratory Studies Facility continued to focus on the excavation of the main drift, south ramp, and testing alcoves.

Exploratory Studies Facility. The excavation of the main drift of the Exploratory Studies Facility was completed and the tunnel boring machine is now tunneling up the south ramp. By the end of the reporting period, the tunnel boring machine had completed 6478 meters and was about 27 calendar days ahead of the 1996 baselined schedule. This performance, however, indicates a slowing from the previous six months of tunneling because of poor rock conditions. During the first half of the reporting period, the tunnel boring machine advanced at an average rate of 21.3 meters per day. By the second half of the reporting period, however, progress had slowed considerably after the tunnel boring machine encountered a zone of highly fractured rock. In June 1996, the Project adopted a new baseline schedule to correspond to the revised draft Program Plan. Under that schedule, the tunnel boring machine is expected to reach the south portal and daylight early in calendar year 1997.

Tunneling was completed in the Exploratory Studies Facility main drift. The tunnel's turn into the south ramp is shown. Completion of the main drift marks a shift in emphasis from excavating the main drift to conducting scientific experiments in the tunnel and alcoves.

The zone of highly fractured rock extends about 1000 meters along the southern part of the main drift. Preliminary evidence indicates that the zone of fracturing does not penetrate the overlying rock units. Questions regarding this zone include the extent and characteristics of the zone and its potential effect on repository layout and flow of water to and through the repository. Studies of the geologic and hydrologic characteristics of this zone will continue as excavation proceeds.

The Project continues to study the geologic and hydrologic characteristics of a zone of highly fractured rock that extends about 1000 meters along the southern part of the main drift.

The designs for the remainder of the Topopah Spring level main drift, south ramp, and south portal pad and facilities were issued to support construction. In addition, designs were issued for the thermal testing facility and the northern and southern Ghost Dance fault access drifts.

Alcove Construction. Construction continued of test alcoves to provide dedicated testing areas to acquire data on the geologic, hydrologic, geochemical, and geothermal characteristics of the site. The initial construction phase of the Thermal Testing Facility was completed in April, and the main access and observation drift for this alcove was completed in May.

The tunnel boring machine progress remains ahead of schedule and alcove construction continues.

Single element heater tests began on schedule in a section of this alcove in August. The second construction phase of this alcove began in late September, and the remainder of the alcove that will be used for the drift-scale heater test should be completed next reporting period. The results of the tests in this alcove will provide information on the response of the ground water and rock to heat generated by electric heaters simulating spent nuclear fuel and high-level radioactive waste.

In late August, the initial phase of construction was completed for the access drift for the first of two alcoves that will provide access to the Ghost Dance fault. An exploratory discovery borehole was drilled into the face of the alcove in an effort to locate the fault. The fault, however, was not located, and the exploratory borehole will be extended in the next reporting period. Once the fault is located, testing will be conducted in the discovery borehole before further excavation. This will allow tests of the relatively undisturbed physical and hydrologic characteristics of the fault. Then the alcove will be excavated through the fault zone to allow direct observation and testing. The second construction phase for the Northern Ghost Dance Fault Alcove, as well as construction of the second alcove (Southern Ghost Dance Fault Alcove), will begin next reporting period.

The Project is using a graded quality assurance approach to focus resources on the most important activities and to eliminate reviews that add little to quality.

Quality Assurance. The Project continued to upgrade its design documents to the graded quality assurance program that was developed and approved last reporting period. The graded approach reduces costs while maintaining quality by focusing resources on the most important activities and eliminating reviews that add little to quality. Specifically, the Project identified activities in Exploratory Studies Facility construction where the

graded approach would be appropriate, revised design specifications to clarify which inspections and tests would provide management with the needed level of confidence, and eliminated unnecessary aspects of field quality control oversight during construction.

EPILOGUE

Since the end of the reporting period, the access drift of the Northern Ghost Dance fault alcove was extended to its planned length of 134 meters, and the exploratory borehole was reentered and extended to locate the fault. Testing also began on the fault. In addition, excavation began on the Thermal Testing Facility drifts that will be used for the drift-scale heater test.

In December 1996, the tunnel boring machine encountered significantly worse ground conditions than had been previously experienced during the excavation of the south ramp. As a result, tunneling progress has slowed substantially. Even with the poor ground conditions, however, the tunnel boring machine is expected to reach the south portal during the second quarter of fiscal year 1997.

On December 16, 1996, the Notice of Public Rulemaking to amend the Department's siting guidelines (10 CFR Part 960) was published in the *Federal Register*. The notice began a public comment period of 60 days. A public hearing was held in Las Vegas on January 23, 1997. The public comment period has subsequently been extended to April 16, 1997.

The Project is re-examining its strategy for evaluating the ability of the Yucca Mountain site to contain and isolate waste, particularly in light of the potentially higher flux rates. The Department expects to issue the detailed strategy late in fiscal year 1997.

CHAPTER 1 - INTRODUCTION

This Site Characterization Progress Report summarizes progress on site characterization activities at Yucca Mountain, Nevada, for the period April 1, 1996, through September 30, 1996. The report is the fifteenth in a series issued approximately every six months to report progress and results of site characterization activities being conducted to evaluate Yucca Mountain as a possible geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste. This progress report is prepared in accordance with Section 113(b)(3) of the Nuclear Waste Policy Act of 1982 (NWPA, 1983), as amended (NWPAA, 1987), and 10 CFR 60.18(g).

This report highlights work started, in progress, and completed during the reporting period. In addition, this report documents and discusses changes to the Office of Civilian Radioactive Waste Management (OCRWM) Site Characterization Program (Program) resulting from the ongoing collection and evaluation of site information, systems analyses, development of repository and waste package designs, and results of performance assessment activities. Details on the activities summarized can be found in the numerous technical reports cited throughout the progress report.

During this reporting period, the OCRWM released its revised Program Plan (DOE, 1996a). Consistent with the objectives and goals outlined in the revised Program Plan, the Yucca Mountain Site Characterization Project (Project) developed and baselined its long-range plan. Site characterization activities have been focused to answer the major open technical issues in accordance with an updated waste containment and isolation strategy. Near-term objectives of the revised Program Plan include updating the U.S. Department of Energy's (DOE) repository siting guidelines to be consistent with a more focused performance-driven program; supporting an assessment by 1998 of the viability of continuing with actions leading to submittal of a Secretarial site recommendation in 2001 and repository license application in 2002. The following sections of Chapter 1 present Project history, outline the bases for the near-term objectives, and discuss the DOE's strategies for achieving these objectives. The chapters after this introduction describe Project activities that occurred during this reporting period.

1.1 HISTORICAL PERSPECTIVE

The Project started in 1977 when the DOE began evaluating the possibility of disposing of high-level radioactive waste in a geologic repository at the Nevada Test Site. Over the next two years, the DOE investigated a number of sites near the Nevada Test Site and decided to concentrate exploration efforts on the tuffs of Yucca Mountain. In 1980, the DOE began a structured, formal investigation to determine whether Yucca Mountain was appropriate for further evaluation. This analysis was conducted to be compatible with the area-to-location phase of site screening described in the national siting plan used before the passage of the Nuclear Waste Policy Act of 1982. As a result of this formal evaluation, the DOE identified Yucca Mountain as a potentially acceptable site in February 1983.

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The Nuclear Waste Policy Act of 1982 established a national policy for the disposal of high-level radioactive waste and spent nuclear fuel. The Act also created the OCRWM within the DOE and assigned that office the responsibility for developing a waste management system.

In response to requirements in Section 112(a) of the Act, the DOE issued the 10 CFR Part 960 guidelines in 1984 for evaluating the suitability of sites for repositories and started the site screening process. The Environmental Assessment for Yucca Mountain (DOE, 1986), also required by the Act, was issued in 1986. In response to the issuance of the Environmental Assessment, surface-based studies at Yucca Mountain accelerated. Initially, these studies consisted of nonsurface-disturbing testing in existing exploratory boreholes and wells controlled by the government; analyses of, and experiments with, rock and water samples; geophysical surveys; meteorological, hydrologic, and seismic monitoring; geologic mapping; and sampling of surficial materials.

With the 1987 Amendments to the Nuclear Waste Policy Act, Congress designated Yucca Mountain as the only site to be characterized to determine its suitability as a geologic repository. During the following year, the OCRWM issued a Site Characterization Plan (SCP) (DOE, 1988) in accordance with the Act and continued conducting a program of detailed site-specific investigations and evaluations to assess the suitability of Yucca Mountain. The U.S. Nuclear Regulatory Commission (NRC) issued its review of the SCP, the Site Characterization Analysis (NRC, 1989), in July 1989. This document identified points requiring clarification and NRC concerns in the form of comments, questions, and objections. From 1989 to 1994, the DOE planned for and then conducted a comprehensive site characterization program based on the SCP.

During the first half of fiscal year (FY) 1994, the DOE conducted preliminary evaluations of various options for restructuring the repository program to meet changing needs and expectations. The 1988 SCP had presented a comprehensive testing, design, and performance assessment program. The scientific information obtained as the Project activities progressed was expected to be used to focus the Program on activities needed for site characterization and safety analysis. However, external and internal pressures since 1988 tended to broaden, rather than to focus the Program, and resulted in rising expectations about the level of certainty in understanding the natural geologic systems and the performance of engineered barriers in the geologic setting. Congress had begun to express concern about continuing growth in the estimated cost of site characterization. In addition, because the site characterization schedule did not require definitive results until the license application was completed in 2001, progress was difficult to demonstrate and to measure. Thus, over the last half of FY 1994, the DOE developed and refined a new approach designed to show early observable progress within the financial resources likely to be available. The 1994 Program Plan, issued December 19, 1994 (DOE, 1994a), summarized the new approach, and the DOE began implementing this new approach during the first half of FY 1995.

By the end of FY 1995, however, Program redirection requested by Congress and consequent reductions in funding for FY 1996 significantly altered the direction of the repository program described in the 1994 Program Plan. The DOE recognized that, because of the significant reduction in funding, a much reduced repository program would be required that,

consistent with Congressional guidance, focused on the core scientific activities at Yucca Mountain and that deferred the preparation and submittal of a license application to the Commission. As a result, the target dates in the 1994 Program Plan for constructing a geologic repository and for emplacing waste underground also were deferred. The funding reductions resulted in curtailed site investigations and postponement of both the environmental impact statement and revisions to the annotated outline for the license application. During the first half of FY 1996, the DOE revised its Program approach to be compatible with congressional guidance and expected funding levels and to answer the most critical technical issues remaining about the design of the repository and its expected performance in the geologic setting. This modified approach reflected the increased technical understanding of the Yucca Mountain site and preserved the key Program objective of submitting a license application within a reasonable amount of time.

1.2 REVISED PROGRAM PLAN

During this reporting period, the DOE released Revision 1 of the Civilian Radioactive Waste Management Program Plan in draft form (DOE, 1996a). This draft Plan, as implemented by the Project's long-range plan (CRWMS M&O, 1996a) and annual fiscal year plans, incorporates a focused, integrated program of site characterization, design, and performance assessment that will result in a license application for a repository at Yucca Mountain, if the site is suitable. As part of its revised Program Plan, the DOE identified three near-term objectives: (1) updating in 1997 the DOE repository siting guidelines to be consistent with a more focused performance-driven program; (2) supporting an assessment by 1998 of the viability of continuing with actions leading to the licensing of a repository; and (3) if the site is suitable, submitting a Secretarial site recommendation to the President in 2001, and a license application to the Commission in 2002. The following sections discuss the near-term objectives identified in the Plan and their background.

1.2.1 Background

The revised Program Plan is based on more than a decade of scientific and engineering work at Yucca Mountain that has advanced technical understanding of the likely performance of a repository at this site. Progress in surface and subsurface investigations over a period of years permits a reduction in the scope of the site characterization program. On the basis of data obtained from numerous boreholes, geologic trenches, and excavation of the Exploratory Studies Facility (ESF), the Project is much more confident in its knowledge and understanding of site conditions. Performance assessments have provided increased confidence that a Yucca Mountain repository will contain and isolate radioactive waste and will meet a reasonable radiological protection standard.

In addition, the DOE continued to refine the strategy for evaluating the ability of the site to contain and isolate waste. This strategy has made it possible to further focus and narrow the remaining work scope needed to support the viability assessment, the evaluation of site

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suitability, and the preparation of a license application for submittal to the NRC. The refined waste containment and isolation strategy under development reflects the acquired knowledge of the site and its natural barriers, as well as the likely influence of site conditions on the performance of potential engineered barriers. The strategy focuses on two technical objectives: first, to limit the annual dose to members of the general public following permanent closure of the repository; and second, to provide total containment of the waste within the emplaced waste packages for thousands of years during the period of highest radionuclide inventory and temperature. The strategy suggests a focused testing and analysis program that would resolve questions about a number of open technical issues. These issues primarily address movement of water through Yucca Mountain, selection of materials for the waste package, and the need for and feasibility of using additional engineered barriers, such as backfill, to enhance overall repository performance. A summary version of the strategy was provided to the Nuclear Waste Technical Review Board and to the NRC in July 1996. A detailed version, including the identification of longer term information needs and work yet to be performed linked to the long-range plan, will be completed in late FY 1997.

1.2.2 Near-Term Objectives

The three near-term objectives identified in the DOE's revised Program Plan are discussed in more detail in the following sections.

1997 Update of Repository Siting Guidelines

A key element in the revised Program strategy is reviewing and revising the DOE repository siting guidelines. The DOE decided to amend these siting guidelines (10 CFR Part 960), which were promulgated in 1984, in response to national policy changes and increasing understanding of the Yucca Mountain site.

Background and Rationale. The Nuclear Waste Policy Act of 1982 set forth the requirements from which the current regulatory framework was developed. The Act required (a) the DOE to issue general guidelines for the recommendation of sites for repository development, (b) the U.S. Environmental Protection Agency (EPA) to promulgate generally applicable standards for the protection of the environment, and (c) the NRC to promulgate technical requirements and criteria to be used for repository licensing. In response to this congressional direction, DOE issued 10 CFR Part 960, the EPA issued 40 CFR Part 191, and the NRC issued 10 CFR Part 60.

Since the regulatory framework for developing geologic repositories was established more than a decade ago, two significant developments have occurred. At the inception of the Civilian Radioactive Waste Management Program, the Nuclear Waste Policy Act of 1982 required the characterization of several potential repository sites in different geologic media. This policy changed when the Nuclear Waste Policy Amendments Act of 1987 directed the DOE to characterize a single site, Yucca Mountain, instead of all three sites being considered at that time.

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The regulatory framework discussed previously was not based on criteria relevant to a specific site, but rather was intended to be applied generically to any potential geologic repository site.

A second change that impacted the regulatory framework occurred when the Energy Policy Act of 1992 (EPAct, 1992) directed the EPA to promulgate a site-specific radiation protection standard for Yucca Mountain. This standard, which is currently being developed, will appear as 40 CFR Part 197, and will be the only such standard applicable to Yucca Mountain. The Energy Policy Act of 1992 also directed the NRC to revise its licensing regulations (10 CFR Part 60) to be consistent with the site-specific standard developed by the EPA.

In addition to the policy developments, the Program has improved its understanding of the conditions at the Yucca Mountain site. Because of this increased understanding and the changes in national policy, the DOE decided to clarify and streamline the siting guidelines. The resulting regulatory framework will provide a more efficient and understandable process for site evaluation and repository development that more clearly focuses on protecting the health and safety of the public.

The Nuclear Waste Policy Act acknowledged that revisions to the siting guidelines might be necessary and authorizes the Secretary of Energy to revise them as needed. These guidelines will be amended through a public rulemaking process that will provide an opportunity for public participation. The DOE must obtain NRC concurrence in any revised guidelines.

Scope of Regulatory Revision. The DOE will use a public rulemaking process to modify 10 CFR Part 960, beginning with a Notice of Proposed Rulemaking that will be issued for public comment. The DOE developed a draft of the Notice of Proposed Rulemaking this reporting period and expects to issue a final rule in 1997. The proposed revisions to the siting guidelines are intended to eliminate the comparative siting criteria for evaluating the suitability of the Yucca Mountain site for development as a repository.

The DOE will propose to evaluate the suitability of Yucca Mountain on the basis of the overall performance of the repository system during operations and after closure, rather than separately evaluating individual aspects of the site. An overall system performance approach is the appropriate method to consider all relevant site features because it identifies in an integrated manner those attributes of the site and engineered components that are most important to the protection of public health and safety. The information gained from the site investigations and the total system performance assessments show that the significance of selected site characteristics should not be judged separately from one another or from a specific design concept. For example, a geologic structural feature that provides a fast pathway for ground-water flow through the mountain may seem to be a detriment when considered alone. When considered in conjunction with a specific repository design, however, the feature may act beneficially by channeling flow away from the waste, thereby reducing the potential for ground-water contact with the waste packages.

While the proposed revision will identify the criteria that will be used by the Program to evaluate the suitability of Yucca Mountain, the details regarding site characterization activities

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and the relationship between the revised testing and analysis plans and the 1988 SCP will continue to be reported in the semiannual progress reports. This reporting period, an expanded appendix (Appendix A) has been added that provides these details.

1998 Viability Assessment

The second principal objective of the revised plan is to address by 1998 the major open technical issues, including those related to the waste containment and isolation strategy, so that an informed assessment can be made of the viability of licensing and constructing a geologic repository at the Yucca Mountain site. The deliverables that contribute to this assessment include the following:

- A package of more specific design work on the critical elements of the repository and the waste package, including a concept of operations that identifies available technologies to accomplish the objectives of geologic disposal
- A total system performance assessment, based upon this design concept and available data, which will describe the probable behavior of the repository system
- A plan and cost estimate for the remaining work required to complete a license application
- An estimate of the costs to construct and operate the repository.

Science, engineering, and management activities are prioritized and integrated to support completing these tasks by 1998. When completed, these deliverables will constitute a logical convergence point at which the Program can make a measurably improved appraisal of the prospects for geologic disposal at the Yucca Mountain site.

Repository and Waste Package Design. The first component of the viability assessment—repository and waste package design—addresses those design elements critical to determining the feasibility and performance of the repository and engineered barrier system. The effort will evaluate the technological feasibility of the designs but will not develop all the detail needed for licensing.

The repository and waste package designs will build on previous work, including the Mined Geologic Disposal System Advanced Conceptual Design Report (CRWMS M&O, 1996b) that was published in March 1996, and will emphasize the open technical issues that affect performance and cost. These issues, based on the waste containment and isolation strategy, arise from thermal management of the waste-generated heat, the role of supplemental engineered barriers, corrosion of waste packages, and dissolution of radioactive wastes. In addition, the design effort addresses safety systems and other factors that significantly affect repository costs.

Scientific and engineering information obtained during testing and analysis of data from the ESF will be incorporated into the designs. Core science and performance assessment

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activities will provide data and criteria for designs. The designs will serve as a basis for estimating repository costs and schedules and for identifying additional design work needed for licensing. The design information will also be used as an input to the next total system performance assessment.

A range of design thermal loads that will accommodate at least the full statutory capacity of a single repository is currently being considered. Alternative thermal loadings will continue to be examined, and design and operational flexibility will be maintained to accommodate new information.

Criticality control for the period following closure of the repository continues to be evaluated to ensure the protection of the health and safety of the public. The near-term objective is to gain sufficient confidence in the Project's criticality approach to support design activities and the viability assessment. The DOE's approach to resolving the criticality issue is detailed in the Disposal Criticality Analysis Methodology Technical Report (CRWMS M&O, 1996c), which was completed this reporting period and an informational copy provided to the NRC staff.

Total System Performance Assessment. The second component of the viability assessment—total system performance assessment—will be based on design concepts and analyses of available site models and data. The assessment will describe the probable behavior of the proposed repository and its ability to meet safety standards.

The latest assessment of the performance of a repository at the Yucca Mountain site, Total System Performance Assessment - 1995 (CRWMS M&O, 1995a), was issued in November 1995. This assessment evaluated repository performance without incorporating the effects of disruptive events, such as volcanism and fault displacement. Earlier analyses showed that disruptive events do not appreciably affect the calculated results. Periodic climate changes, however, were included in the analyses in terms of potential changes in both infiltration rate and water table elevation. The latest assessment used more representative conceptual models of the site. More importantly, it also incorporated more realistic models for the behavior of the engineered system.

The next assessment of system performance, scheduled for completion in FY 1998, will be based more directly on the process-level models that are being developed for the site and engineered system. A biosphere model is also expected to be in place that will allow more representative calculation of dose and the associated risk to a representative individual in an affected population. The objective for this assessment is to evaluate both the expected performance of the system and its performance under conditions imposed by potentially disruptive events, considering appropriate ranges of probabilities of occurrence and of consequences.

The 1997-1998 performance assessment will reflect an integrated site and engineered system using data available at that time. Uncertainties will continue to exist in the characterization of both the engineered component and natural system processes. These uncertainties will be reflected in the alternative conceptual models and parameter distributions

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considered in the analyses. Thus, the performance assessment also will evaluate the possible range of performance caused by uncertainty in key factors, such as ground-water flow, thermal effects, and corrosion.

A phased peer review of the performance assessment results will begin early next fiscal year, and detailed planning for the review has already begun. The comments and recommendations from the early review stages will be incorporated, as appropriate, in the total system performance assessment developed for the viability assessment. Later, if the site is determined to be viable, the comments and recommendations will be incorporated into the assessment that will support site recommendation and preparation of the license application.

License Application Plan. The third component of the viability assessment—license application plan—will define the scope, schedules, costs, and remaining work required to complete a license application. Submittal and docketing of a license application to the NRC, should the Yucca Mountain site be found suitable, is the DOE's central goal.

The license application plan will describe the information needed for the NRC to review the Program's request for construction authorization for the repository and will guide the development of the license application. Work on the plan will begin next reporting period, with completion scheduled for the end of FY 1997. In identifying the information needed within the framework of the waste containment and isolation strategy, the Program will draw on the models and data that describe the natural system, the repository and waste package design, and the total system performance assessment. The plan will describe a testing and analysis program that needs to be completed before the initial license application can be submitted. This testing and analysis program will also support safety assessments for a specific repository design. The plan also will describe the performance confirmation program needed during construction and operation to further reduce the uncertainties in long-term performance of the repository. The plan will identify additional design and performance assessment activities needed to support the license application. Finally, the plan will define a schedule and estimate the cost needed to complete the license application.

Cost and Schedule Estimates. A set of estimated costs and schedules for the repository system is the fourth component of the viability assessment. The estimates will encompass completion of site characterization, performance confirmation, and construction, operation, and closure of a repository. The life-cycle cost and schedule estimates will be a factor in policy decisions regarding the feasibility of and justification for continuing with the licensing and construction of a geologic repository.

The estimates will be based on the repository and waste package designs developed for the viability assessment and on scientific testing and analyses completed by 1998. Because not all the details of the design will be developed fully by the 1998 viability assessment, some design assumptions will be used to complete the estimates.

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Site Recommendation and License Application

If the site is determined to be suitable, the DOE would proceed with issuing the statutorily required environmental impact statement and Secretarial recommendation to the President. If the site were approved by the President and Congress, the DOE would submit a license application to the NRC in 2002. The work completed for the viability assessment will provide a foundation for the work that would follow.

Environmental Impact Statement. The Nuclear Waste Policy Act of 1982, as amended, requires that a final environmental impact statement accompany any Secretarial site recommendation to the President. Any such environmental impact statement would be adopted to the extent practicable by the NRC in connection with issuance of a construction authorization and license. The environmental impact statement process began with the Notice of Intent published in the *Federal Register* on August 7, 1995. The public comment period closed December 5, 1995, following 15 public meetings across the nation. Because of decreased Project funding for FY 1996 and direction provided by Congress in that fiscal year appropriation, preparation of the environmental impact statement was deferred until FY 1997. The revised Project schedule shows that, after the viability assessment, the draft environmental impact statement would be issued in FY 1999 and the final environmental impact statement would be issued in FY 2000.

Site Recommendation. If the site is determined to be suitable with respect to the revised siting guidelines, a decision to recommend to the President that the site be approved for development as the nation's first high-level waste repository is expected in FY 2001. In FY 2000, the DOE would publish a Notice of Consideration to inform the public and would announce a schedule for public hearings on the possible site recommendation. After the hearings and before recommending the site to the President, the DOE would notify the State of Nevada about the decision to recommend the site.

As required by Section 114 of the Nuclear Waste Policy Act of 1982, the basis for the decision on the site recommendation would include (a) a description of the proposed repository, including preliminary engineering specifications; (b) a description of the waste form or packaging and an explanation of the relationship between the geologic environment and the waste packages and waste forms; (c) a discussion of data obtained during site characterization relating to the safety of the site; (d) the final environmental impact statement; and (e) preliminary comments by the NRC concerning the sufficiency of site characterization. The site recommendation also would include the views and comments of the Governor of the State of Nevada, the State legislature, and any affected Indian tribe, as well as other information the Secretary of Energy considers appropriate and any impact report submitted by the State.

A Project Integrated Safety Assessment, scheduled to be completed in 1998, will present integrated information about the technical elements of the Program. This document will describe and integrate information on site conditions, repository and waste package design, and performance assessment. After completion, the document will be provided to the NRC for review as one basis for its preliminary comments on the sufficiency of information on the site

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and design for inclusion in a license application. The Project Integrated Safety Assessment will be used as the starting point for developing the license application.

License Application and Revised Approach to Licensing. Review and approval of Revision 1 of the License Application Annotated Outline (DOE, 1995a) and further action on the Licensing Support System were deferred during FY 1996. Work on the Licensing Support System is scheduled to begin again in FY 1997, but no further iterations of the annotated outline are planned.

The goal of submitting a successful license application remains central to the Program's mission. The products associated with the viability assessment will help improve understanding of the repository concept, and provide a comprehensive appraisal of the prospects for licensing and constructing a geologic repository at Yucca Mountain. Although the information will not be sufficient for licensing, this work is a logical step toward developing a first-of-a-kind repository. In completing the assessment, the Project will define a repository concept that includes a facility and waste package design consistent with the characteristics of the Yucca Mountain site and will assess the performance of this repository. In so doing, the Project will examine alternatives and will propose the best repository system that can be achieved within rational cost and schedule restraints. Appropriately, the DOE will develop a repository concept and ensure that it adequately protects public health and safety before seeking approval from outside parties.

The DOE believes that interactions with the NRC staff will focus on two objectives: reaching a common understanding regarding the issues that are significant to overall repository performance, and reaching agreement on the adequacy of proposed methodologies and approaches to address important technical issues such as criticality control and seismic design. The goal is to reach a mutual understanding of the repository concept as it develops. This understanding will provide a basis for NRC preliminary comments on the sufficiency of site characterization and design for inclusion in a license application.

This approach is a departure from previous efforts that focused on resolving individual issues related to specific site characteristics in isolation from one another or from a specific design concept. The DOE believes the sufficiency of site characterization data and analyses can only be determined within the context of a coherent repository concept that includes both design and system performance. Thus, the DOE will first develop the overall repository concept before addressing specific issues related to licensing. The DOE will seek insights from the NRC staff throughout this process regarding issues affecting licensing and approaches and methodologies for addressing specific technical issues.

To support the NRC licensing review, the Project would acquire a computer-based Licensing Support System in FY 1999. That system would undergo an acceptance test meeting the requirements of the NRC's Licensing Support System Administrator. The system would allow access to the comprehensive documentation required for the licensing proceedings. The DOE is required by 10 CFR 2.1003 to obtain NRC certification of compliance of the licensing support system at least six months before the license application is submitted to the NRC, currently scheduled for FY 2002.

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The current strategy recognizes that additional information would be obtained through continued surveillance, measurement, testing, analysis, and performance assessment during the construction and operation of the repository. This information would be reflected in subsequent license application updates and amendments.

Beyond license application submittal, the DOE would place high priority on those tests designed to enhance confidence about long-term performance as part of the performance confirmation program required under 10 CFR Part 60, Subpart F. During this time, the long-duration in situ tests that measure moisture redistribution and changes in rock properties in response to thermal loading would provide key information. The Project also would give high priority to confirming the behavior of engineered barriers within the range of expected repository conditions.

If the NRC issues a license to receive and possess spent nuclear fuel and high-level radioactive waste, the scientific work will focus on obtaining data on changes to the site caused by repository construction and waste emplacement. The objective will be to confirm, in accordance with 10 CFR 60.140(a), the basis for earlier predictions about containment and isolation, to confirm that natural and engineered systems are functioning as expected, and to test the models that will be relied upon for confirming the long-term predictions required to support a decision by NRC to permit closure of the repository. The application for a license amendment to close the repository will not be submitted until sufficient confirmatory test information is available to provide adequate confidence to support a decision to close the repository. The repository will be designed and operated to preserve the option to retrieve the emplaced waste for up to 100 years after the beginning of waste emplacement, or until the Commission decides to permit permanent closure. A decision to exercise the retrieval option may be made on the basis of the results from performance confirmation, or it may be prompted by a policy decision related to geologic disposal of spent nuclear fuel.

1.3 PROGRESS REPORT CONTENT

As shown in the box on this page, the main chapters of the progress report deal with programmatic, site, design and construction, and performance assessment activities. Various appendixes support the main text. This report reflects the information available and the status of the Project as of September 30, 1996. An Epilogue has been added at the end of the Executive Summary to identify important events occurring after the close of the reporting period and before the report is printed.

In addition, for more general readers, the report begins with a Note to Readers that summarizes major achievements during the reporting period. The Executive Summary is a summary of major decisions, accomplishments, and issues of interest during the reporting period.

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Chapter 2	Programmatic Activities
Chapter 3	Site Programs
Chapter 4	Repository Design
Chapter 5	Waste Package
Chapter 6	Performance Assessment Program
Chapter 7	Exploratory Studies Facility Design and Construction
Appendix A	Documentation of Changes to the Program since the Site Characterization Plan was Issued
Appendix B	Regulatory and Management Document Progress
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Appendix I	Tables of Technical Computer Codes
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CHAPTER 2 - PROGRAMMATIC ACTIVITIES

This chapter reports the results of the Yucca Mountain Site Characterization Project (Project) planning and regulatory activities, including baseline control, environmental compliance, and licensing. Other programmatic activities reported include those in quality assurance (QA) and public outreach. Programmatic activities focus, evaluate, plan, control, and ensure the quality of site characterization, design, and performance assessment activities.

Programmatic activities this period focused on supporting the goals and objectives in the revised Program Plan released this reporting period by the U.S. Department of Energy (DOE, 1996a). As discussed in Chapter 1, the revised Program Plan identifies a repository program refocused to address the major unresolved technical questions regarding the conceptual design of the repository and its expected performance in the geologic setting. The following summarizes the notable programmatic accomplishments during this reporting period.

In line with the goals of the revised Program Plan, the DOE developed a draft Notice of Proposed Rulemaking to amend the repository siting process. The proposed amendment would clarify and simplify the procedural aspects of the siting process and the criteria the DOE will follow in evaluating whether the site at Yucca Mountain is suitable for a geologic repository. In other planning and control activities, the Project baselined its long-range plan (CRWMS M&O, 1996a) in June 1996 and developed detailed annual planning for fiscal year (FY) 1997 (CRWMS M&O, 1996d).

In regulatory activities, the U.S. Nuclear Regulatory Commission (NRC) staff informed the DOE that sufficient information exists to close all comments on Seismic Topical Report I (DOE, 1994b). The DOE completed a draft of the Disposal Criticality Analysis Methodology Technical Report (CRWMS M&O, 1996c). This report provides a preliminary description of DOE's proposed risk-based disposal criticality analysis methodology.

Details on these and other programmatic activities are presented in the rest of the chapter.

2.1 PROJECT PLANNING AND BASELINE CONTROL

The Office of Civilian Radioactive Waste Management (OCRWM) released Revision 1 to its Program Plan in draft form in May 1996. Consistent with that revision, the Project baselined its long-range plan in June 1996 using the congressional budget request approved by the administration. That plan outlines activities extending through a FY 2002 submittal of a license application to the NRC for repository construction authorization. Additionally, late in the reporting period the Project baselined its detailed FY 1997 work scope and funding plan.

2.1.1 Project Planning and Scheduling

During the last half of FY 1996, a major replanning effort was completed. The replanning effort, which began last reporting period, is presented in Revision 1 to the OCRWM Program Plan (described in Chapter 1) and was undertaken as a result of congressional guidance associated with the fiscal year budget appropriations.

Consistent with the new Program Plan goals and objectives, the Project revised its long-range plan and further developed its detailed annual planning for FY 1997. The long-range plan compiles the assumptions, work scopes, schedules, milestones, deliverables, cost estimates, and risks associated with implementing the Yucca Mountain Site Characterization Project (CRWMS M&O, 1996a). The plan covers activities planned for the next fiscal year through the FY 2002 submission of the license application. As a part of the long-range planning process, the Project developed the Integrated Project Schedule, which is a multiyear logic network of activities and participant-level milestones. This schedule, which includes all technical, support, and programmatic activities, is used to identify a set of activities necessary to develop a credible viability assessment, environmental impact statement, site recommendation, and license application. The Integrated Project Schedule also analyzes critical paths and helps to identify impacts of funding constraints. Also during this reporting period, the Project further developed the long-range planning information into detailed annual planning for FY 1997. The Project presented an overview of the long-range planning basis to the NRC staff in a technical exchange on August 15, 1996.

Forecast: During the first half of FY 1997, the Project will update its long-range plan baseline to reflect results of detailed annual planning and any additional congressional guidance. Detailed annual planning will be completed for FY 1998 work scope to ensure a well-defined and measurable path to the viability assessment.

2.1.2 Independent Management and Financial Review

As reported in Progress Report #14 (DOE, 1996b), an independent management and financial review of the Project was completed during the last half of FY 1995 (Peterson, 1995). The review identified concerns about the Project and made recommendations in four areas: organization effectiveness, financial and contract management, schedules and credibility of milestones, and funding levels and funding priorities.

The report contained 65 recommendations. A total of 47 recommendations were implemented. The remaining recommendations are not within the control of the Program.

Forecast: No further action is required.

2.1.3 Document Hierarchy and Program Baseline

The Civilian Radioactive Waste Management System (CRWMS) Document Hierarchy for OCRWM identifies both Program- and Project-level documents, including both regulatory and management documents. During the previous reporting period, a Technical Baseline Hierarchy Task Group was formed to simplify the hierarchy. The final recommendations of the task group will directly affect the requirements documents listed in Appendix B.

2.1.3.1 Regulatory and Management Controls

Changes in Project-level documents that control both regulatory and management activities were made to reflect the revised Program Plan. In addition, the Mined Geologic Disposal System Requirements Document (DOE, 1996c) was changed to accommodate a variety of cask/canister systems for spent nuclear fuel; and the process was begun to incorporate DOE-owned spent nuclear fuel into the document. The Controlled Design Assumptions Document (CRWMS M&O, 1996e) was changed to incorporate changes to the technical baseline during FY 1996. Changes to several documents, however, are on hold pending the recommendations from the Technical Baseline Hierarchy Task Group. The changes in Project-level documents that control both regulatory and management activities as identified in the current CRWMS Document Hierarchy are summarized in Appendix B.

2.1.3.2 Change Control Board Actions

The Project Change Control Board evaluates proposed changes to the Project technical, cost, and schedule baselines. If the proposed change is approved, a Change Directive is issued and the change is implemented by affected organizations in accordance with specific directions listed in the directive.

Appendix C presents a table summarizing the key Project Change Control Board actions completed during this reporting period. These actions affected baseline documents, work breakdown structures, cost, schedule or work scope activities, surface-based testing, and the Exploratory Studies Facility (ESF).

Some of the most noteworthy changes were to authorize continuation of the tunnel boring machine through completion of the ESF, to allow acceleration of testing on the northern Ghost Dance fault geothermal borehole, to modify the FY 1996 baseline in support of the development of the long-range plan, and to revise the Project cost and schedule baseline to reflect the revised Program Plan.

Forecast: The recommendations of the Technical Baseline Hierarchy Task Group will be used when they become available.

2.2 REGULATORY ACTIVITIES

Regulatory activities associated with suitability, environmental compliance, and licensing (including interactions with the NRC) continued this period to support the redirection of the Program and the development of Program Plan Revision 1.

2.2.1 Suitability Activities

During the current reporting period, the DOE developed a draft Notice of Proposed Rulemaking to amend 10 CFR Part 960 by adding a new site-specific subpart for Yucca Mountain. The proposed amendment would, in part, eliminate evaluation of the discrete technical guidelines. The suitability of the site for development as a repository would be based on determinations of compliance with two system guidelines, a postclosure system guideline, and a preclosure radiological safety system guideline.

Forecast: The Notice of Proposed Rulemaking will be published in the *Federal Register* and will be followed by a period of public comment and public hearings. Following the resolution of the public comments, the amended regulation will be submitted to the NRC for concurrence. A final rule is expected in late FY 1997.

2.2.2 Environmental Compliance Activities

During the reporting period, numerous environmental surveys and permitting actions were completed for new and planned site characterization activities at Yucca Mountain. Progress in these areas is reported in this section.

2.2.2.1 Permits

Permits are required for some activities having potential environmental impacts. This section discusses the progress or activity associated with these permits.

Water Quality

The Nevada Department of Health evaluated the ESF potable water system, confirmed its acceptability, and issued a public water system permit. On April 26, 1996, following laboratory verification of proper disinfection, use of the potable water system and the septic leachate system commenced.

On April 26, 1996, the permanent ESF medical trailer became fully operational with connections to both the ESF potable water system and the septic leachate system. Operation of the temporary medical facility was discontinued on April 26, 1996.

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Forecast: Water quality permit reports will continue for FY 1997, as required.

Air Quality

Pursuant to the requirements of Air Quality Permit #AP9611-0573, a request to extend the 500-kW diesel generator construction deadline was made to the State of Nevada to allow construction activities to begin during the first half of FY 1997. Under the same air quality permit, the cancellation of the Commander crushing and screening plant was also requested because the equipment was not expected to be used.

On July 10, 1996, a revised Air Quality Permit #AP9611-0573 was received. The revised permit included numerous clerical corrections and the following changes: (a) the addition of the grout batch plant, (b) the cancellation of the Commander crushing and screening plant, (c) the requested one-year extension to construct the 500-kW diesel generator system, and (d) a revision to the ESF radial stacker location granting permanent relocation of the stacker at tower #1 for the duration of the Project.

Because of funding limitations, the Air Quality Permit AP#9999-0612 for the bioremediation cell was canceled.

Forecast: Because of changing Project needs, air emission sources are projected to be reduced in the first half of FY 1997. The elimination or reduction of point sources or emissions will require a revision to the Air Quality Permit #AP9611-0573. The submission of new air quality operations permit applications will continue for FY 1997, as needed.

Underground Injection - Drilling and Tracers

Three tracer tests were requested for the C-hole complex. These tests were conducted to evaluate hydrogeologic properties of the Bullfrog Tuff. Tracers currently approved under the Underground Injection Control Permit UNEV89031 were used. Approval was granted by the State of Nevada to conduct the following tests:

1. Injection of sodium iodide in borehole UE-25 c#2 at the C-hole complex. Injection occurred on February 8, 1996.
2. Injection of pentafluorobenzoic acid in borehole UE-25 c#2 at the C-hole complex. Injection occurred on May 15, 1996.
3. Injection of sodium iodide in borehole UE-25 c#1 at the C-hole complex. Injection occurred on June 18, 1996.
4. Injection of lithium bromide, pentafluorobenzoic acid, and fluorescent microspheres in borehole UE-25 c#2 at the C-hole complex. State approval is expected early in FY 1997.

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A request was submitted to the State of Nevada for approval to install a SEAMIST liner in borehole USW UZ-14. Approval is expected early in FY 1997. The SEAMIST liner is a temporary instrument capable of providing ambient pneumatic data. The device consists of an inflatable liner equipped with ports and hoses designed for various sampling purposes. The liner may be positioned downhole, inflated at the desired depth, then deflated for removal.

On April 24, the State of Nevada granted approval to inject sulfur hexafluoride tracer into the ESF ventilation system to evaluate its ventilation capabilities. The ventilation test was conducted on April 25, 1996, using 1.5 cubic feet of sulfur hexafluoride. On September 16, 1996, a second ventilation tracer test was requested. For the second test, the use of 3.0 cubic feet of sulfur hexafluoride was requested. Approval is expected early in FY 1997.

Forecast: Submittal of additional underground injection control tracer test requests for the C-hole complex will continue through the first half of FY 1997, as needed. A letter proposing the use of oil skimmer-treated water for dust control will be sent to the State of Nevada early in FY 1997.

2.2.2.2 Environmental, Safety and Health Assessments

Comprehensive and focused, special-issue environmental, safety and health assessments are performed under the Project's assessment program. Comprehensive assessments evaluate all aspects of an environmental, safety, and health program for a specific Project organization, or the environment, safety, and health aspects of a specific Project-wide program. Focused special-issue assessments provide a quick response capability for evaluating high-priority environment, safety, and health concerns or areas of interest. These assessments provide oversight of Project organizations and activities to ensure compliance with Federal and State statutory requirements, DOE Orders, and Project plans and procedures. Both comprehensive assessments and focused, special-issue assessments were conducted in the second half of FY 1996.

Forecast: Two comprehensive and four focused, special-issue assessments are planned for the first half of FY 1997.

2.2.2.3 Environmental Surveillances

Approximately 120 environmental surveillances were conducted at the Yucca Mountain site to ensure compliance with environmental, programmatic, and permit requirements. Corrective action and follow-up work were required on 30 (25 percent) of the surveillances, and 21 (about 70 percent) of those follow-up activities were completed during this reporting period.

Forecast: Two hundred surveillances are projected for the first half of FY 1997. Remaining corrective action and follow-up work from the second half of FY 1996 will be completed during the first half of FY 1997.

2.2.2.4 Preactivity Surveys

During this reporting period, one land access and environmental compliance activity review was completed. This process involves acquiring land access approvals and right-of-way reservations and completing environmental preactivity surveys (which include archaeological, biological, and in certain instances, radiological surveys) before each Project site activity can be initiated. During the second half of FY 1996, four requests to initiate preactivity surveys were received. Four partially completed preactivity surveys were canceled because of diminished funding, and one activity was granted casual access.

Forecast: Approximately three land access and environmental compliance activity reviews are expected to be completed during the first half of FY 1997.

2.2.2.5 Land Acquisition and Site Access

Four new participant requests to initiate site characterization activities were received during this reporting period. One request (Installation of ESF South Portal Pad and Access Road) was completed and access authorization was granted. Two requests (Installation of UNRSL Seismic Instrumentation in Y-Tunnel and Post Activity Survey for Four Seismic Stations) are awaiting Nevada Test Site Operations Permits. One other request (Amargosa Desert Digital Seismic Station for Southern Great Basin Seismic Network) is awaiting a right-of-way reservation from the Bureau of Land Management.

Two requests from the last reporting period were completed. The U.S. Geological Survey (USGS) Seismic Station - Boulder City request was completed with the receipt of a special use permit from the National Park Service and access authorization was granted. The Timber Mountain and Thirsty Mountain Seismic Stations request was completed with the receipt of a right-of-way reservation from the Bureau of Land Management and access authorization was granted.

Forecast: Four to six land access and environmental compliance activity reviews are expected to be completed during the first half of FY 1997.

2.2.3 Licensing Activities

The DOE's eventual goal is the issuance of the necessary licenses and permits for the repository, if the site is found suitable. In pursuit of this goal, licensing activities included the management of and participation in interactions with the NRC and other oversight organizations. These interactions help to clarify regulatory and technical issues and to reach a common understanding of regulatory requirements.

2.2.3.1 Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations

This section reviews and discusses significant actions, agreements, and accomplishments that resulted from interactions between the DOE and the NRC, meetings of the Advisory Committee on Nuclear Waste, and meetings of the Nuclear Waste Technical Review Board. Appendix D tabulates the interactions with each of these agencies.

U.S. Nuclear Regulatory Commission

Between April 1996 and September 1996, the DOE participated in several interactions with the NRC, including two technical exchanges, one on Total System Performance Assessment - 1995 (CRWMS M&O, 1995a) and one on DOE's long-range plans. In addition, there were two technical meetings on ESF construction and design status, and three management meetings. Numerous informal interactions also occurred between DOE personnel and NRC onsite representatives, including regularly scheduled meetings with the YMSCO Project Manager and Assistant Managers and three Appendix 7 meetings, one on Seismic Topical Report II (DOE, 1995b), one on tectonics models, and one on ESF thermal tests. Appendix 7 meetings are informal meetings conducted under the procedures outlined in Appendix 7 of a procedural agreement between NRC and DOE on the principles for interface during geologic site investigation and site characterization (DOE, 1993a). Appendix 7 deals specifically with NRC onsite representatives.

At a May 22-23, 1996, technical exchange, the NRC staff and its Center for Nuclear Waste Regulatory Analyses staff presented the results of selected aspects of their audit review of Total System Performance Assessment - 1995. The NRC used the DOE's waste containment and isolation strategy in their audit review to identify five focus areas examined during the audit review. The selected topics for discussion included subsystem abstractions, infiltration rates, dilution factors, waste package failure modes, and calculations of temperature and relative humidity. The NRC staff presentations outlined areas of concern and disagreement with methods, assumptions, and results of Total System Performance Assessment - 1995. These presentations led to the identification of key questions and discussion topics for each of the five audit areas and the formation of two working groups to discuss these topics. The working group discussions dealt with topics related to container life, source term and thermal effects, infiltration, deep percolation, and model abstraction. The exchange resulted in a better understanding of which technical issues each agency considered important. Both the NRC and the DOE are moving toward using total system performance assessment as the primary tool to demonstrate compliance with requirements.

On August 15, 1996, the NRC and the DOE conducted a technical exchange to discuss and describe YMSCO's Long-Range Plan (CRWMS M&O, 1996a). The purpose of this interaction was to provide orientation and an overview both of the scope of the long-range plan and activities associated with its development, and of the FY 1997 annual plan. Specifically, presentations provided by DOE included (a) status and development history of the waste containment and isolation strategy and the overall licensing strategy; (b) activities planned for the

next two years, mainly sensitivity and uncertainty analyses using process models, to support the total system performance assessment supporting the viability assessment; (c) examples of differences between the 1994 Program Plan and the long-range plan; (d) the single-pass engineering design strategy; (e) key schedule elements and major milestones for the environmental impact statement part of the National Environmental Policy Act process; and (f) main elements for the development of the licensing support system. The interaction paved the way for the NRC staff to better understand the Project's long-range plan.

The DOE and the NRC staff conducted technical meetings on June 3, 1996, and September 12, 1996, to discuss the status of ESF construction, design, and ESF-related site characterization activities and to resolve identified issues. Other major topics addressed during the June 3, 1996, technical meeting included an update on the ESF heater test design details; goals and status of ESF fracture and fault data; the DOE's response to the NRC letter dated December 14, 1995 (NRC, 1995a), concerning the Regulatory Compliance Review Report and ESF requirements flowdown and traceability; and repository design detail at license application and development of engineering schedules and methods of prioritizing work. In further discussions during the September 12, 1996, meeting the DOE presented the status of ESF construction and testing, described the engineering design program, and presented an overview of a DOE report concerning the spent nuclear fuel thermal conductivity. Specifically, during this meeting questions and comments were discussed concerning the single-heater thermal test, drift-scale thermal test, planned excavation method of the Thermal Testing Facility, instrumentation and data acquisition, and modeling of the involved processes. Several preliminary concerns of NRC regarding the excavation method used for the thermal testing alcove and the representativeness of the thermal test location were addressed by the DOE staff.

The DOE and the NRC hold periodic management meetings to provide a forum for management-level discussions of issues and concerns associated with the Project and other aspects of the CRWMS program. A number of topics were discussed in meetings held on May 8, 1996, and July 1, 1996. The topics included budget, legislation status, and the revised Program Plan; perspectives of preclosing interactions with the NRC; an update on U.S. Environmental Protection Agency (EPA) standards and revisions to 10 CFR Part 60; the licensing support system; the DOE and the NRC interactions procedural agreement and lessons learned from the revised approach to interactions; waste containment and isolation strategy; documenting the basis and rationale for Project-related DOE decisions; and the NRC's key technical issues implementation plans.

In addition to the formal interactions with the NRC staff, regular informal interactions with the NRC onsite representatives and Appendix 7 meetings were conducted to discuss and maintain communication with the NRC staff on technical and programmatic matters of interest to both agencies. On April 23, 1996, the DOE and the NRC conducted an Appendix 7 meeting on Seismic Topical Report II at the offices of the Center for Nuclear Waste Regulatory Analyses, in San Antonio, Texas, to discuss the staff's review comments (NRC, 1996a) on DOE's Seismic Topical Report II (DOE, 1995b). Two items were on the agenda of this meeting: (1) discussion of the DOE's planned preclosure seismic design methodology for underground repository facilities and (2) the DOE's plans for revising Seismic Topical Report II in response to the NRC

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staff's review comments. A significant point of discussion at this meeting was the potential third seismic topical report. The NRC staff expects the DOE to prepare this report, which would present the results of applying the probabilistic seismic hazards assessment methodology described in Seismic Topical Report I (DOE, 1994b) and the preclosure seismic design methodology described in Seismic Topical Report II. The DOE, however, is not committed to writing a third seismic topical report and may submit the information to the NRC staff for informal review in the form of an internal design study report.

On May 7-8, 1996, the DOE and the NRC conducted an Appendix 7 meeting at the facilities of Southwest Research Institute in Texas. The purpose of the meeting was to exchange information on various conceptual tectonic models applicable to Yucca Mountain. The DOE presented the status of tectonic modeling and the contributions of geophysics and surface mapping to the modeling. Several conceptual tectonic models were reviewed and discussed in this interaction. The NRC noted that this meeting was useful in achieving a focus on pertinent tectonic models.

An Appendix 7 meeting and site visit was held on July 24, 1996, at the ESF. The main objectives of this meeting and site visit were to provide an opportunity for the NRC staff to visit the Thermal Testing Facility before the DOE insulates the single-heater test block, to discuss with the principal investigators the scope and purpose of current and planned thermal testing, and to work toward a common understanding of thermal test data needs for the viability assessment and license application. Major areas of NRC staff interest included test design and supporting calculations for the single-heater test, representativeness of test locations, sufficiency and adequacy of thermal test data for the viability assessment and license application, and interference between individual tests and between construction and tests. Other topics discussed included the single-heater test procedures, physical set-up of the test block, instrumentation details, and characterization of the heater block and testing details pertaining to different aspects of thermal, thermomechanical, thermohydrological and thermohydrochemical in situ testing. The DOE also addressed two NRC questions regarding the representativeness of the test location and the impact of the alcove excavation method on test results. These topics are subject to further discussions during the future ESF technical meetings.

On September 10, 1996, an Appendix 7 meeting was held in Las Vegas, Nevada, to review and discuss DOE's expert-elicitation report process and documentation associated with the probabilistic volcanic hazards analysis. The NRC staff formulated its review and feedback around the steps involved in the documentation process. Discussion and dialog on each step involved a series of questions and answers. Lessons learned from this meeting will be used by DOE to improve upon future expert elicitation.

Advisory Committee on Nuclear Waste

The DOE's participation in the NRC's Advisory Committee on Nuclear Waste meetings was limited during this period. However, DOE staff members attended four meetings conducted in Rockville, Maryland, and one meeting in Las Vegas, Nevada. The following presents highlights from those meetings.

During the 83rd meeting, held May 15, 1996, the NRC staff discussed items of current interest related to the NRC Division of Waste Management programs, including progress at the Yucca Mountain site, issue resolution process, and status of NRC key technical issues. The NRC staff reported on the chlorine-36 found at several locations at Yucca Mountain associated with faults and fractures in the ESF (Topopah Spring). Both the advisory committee and NRC staff agreed that the presence of chlorine-36 was expected. Dr. Hinze (advisory committee member) expressed concerns that testing at the C-hole complex might be discontinued before the broad scope of testing described in the study plan was completed and that this was the only opportunity to obtain the data from the saturated zone. This concern was related to the need for DOE to document its decisions related to stopping a testing program and changes in the Project's plans in general. The Committee appeared to agree with the NRC staff that DOE needs to document these decisions and to share the information with committee members to get feedback on the adequacy of information for the repository license application.

The main items of interest during the 84th Advisory Committee on Nuclear Waste meeting, held June 25-26, 1996, were a discussion of the critical group and reference biosphere for use in dose calculations, a review by the NRC staff of Total System Performance Assessment - 1995, a presentation by DOE on the revised Program Plan, and a briefing by the advisory committee to the Commissioners on current activities. On the basis of discussions by representatives from the National Academy of Sciences, EPA, and the Electric Power Research Institute, there was general agreement that the critical group and reference biosphere for the postclosure period at Yucca Mountain should be specified by rulemaking to avoid related challenges during licensing. There was also agreement that the specifications should be broadly related to characteristics of today's society to avoid undue speculation about future societies. The EPA is expected to provide general requirements and the NRC then will use site-specific data to further define the critical group and reference biosphere. The DOE, whose position has been expressed in letters to the EPA, did not offer further comments on this topic. Also, the DOE presented the background and rationale for revising the Program Plan and other activities (including the Integrated Planning Process and the Project Integrated Safety Assessment) and summarized the Program focus and changes. In response to an advisory committee question on DOE-NRC interactions before the viability assessment, DOE explained that meetings will be held only when progress can be made on issues important to repository performance.

The 85th Advisory Committee on Nuclear Waste meeting held on August 21-22, 1996, included a workshop on NRC activities related to coupled processes that could affect preclosure and postclosure performance at Yucca Mountain. The DOE did not make formal presentations on the subject, but staff members were available to clarify results and plans. Although the NRC and the DOE programs are broadly similar, some differences exist. One such difference is that the NRC staff plan to evaluate coupled processes resulting from volcanic and seismic events, whereas these evaluations do not have a high priority in DOE's program because available data did not indicate that these events are significant. Another discussion topic at the meeting was the NRC Branch Technical Position and guidance on expert elicitation. The NRC noted that the DOE and NRC seem to have consistent positions and that the DOE has no substantive disagreements with the staff's technical positions. The NRC staff also accepted and agreed with

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the DOE's main comment that additional guidance on the use of expert elicitation in the area of performance assessment was not necessary.

The 86th meeting of the Advisory Committee on Nuclear Waste was held September 26-27, 1996, in Las Vegas, Nevada. A principal discussion topic was flow and transport of radionuclides at Yucca Mountain, including evidence from chlorine-36 studies and potentially higher percolation flux rates. Topics discussed were fracture flow, geochemical effects on radionuclide transport, the role of fracture coatings and colloids on radionuclide transport, and integrated transport modeling. Other meeting topics included site characterization integration through the use of performance assessment and repository design for the viability assessment. The committee toured the ESF and Amargosa Valley.

Nuclear Waste Technical Review Board

A full board meeting of the Nuclear Waste Technical Review Board was held in Austin, Texas, April 30 to May 1, 1996. The main topic of the meeting was planning and integration of the OCRWM program. The first day focused on the integration of major program activities (i.e., surface-based testing, underground exploration, repository design, performance assessment, and health and safety) and the priorities used to define tasks and to allocate resources. Of particular interest to the Board was the relationship of the major program elements and the rationale underlying those relationships, such as the waste containment and isolation strategy and insights from performance assessment that guide the program and repository design, and the rationale underlying the decisions that are being made regarding exploration and testing priorities. The second day included updates on the ESF and the scientific program. A round-table discussion of all the meeting topics concluded the session.

The summer full board meeting of the Nuclear Waste Technical Review Board was held in Denver, Colorado, July 9-10, 1996. The meeting focused on two main issues: exploration and testing activities at Yucca Mountain, and past and future climate and hydrology at Yucca Mountain. Specific topics discussed at the meeting related to the ESF included updates on the tunnel boring machine operations and scientific investigations, lessons learned from ESF exploration to date, and the status of the DOE's waste containment and isolation strategy and thermal testing. Topics related to climate and hydrology included the geological structure at Yucca Mountain, historical perspectives and current views on climate and hydrology, and climate modeling. On the second day, a round-table discussion covered all topics covered during the meeting. Presentations were made by the DOE and its Management and Operating Contractor (M&O), plus representatives from the USGS, the U.S. Bureau of Reclamation, the University of Arizona, and the National Center for Atmospheric Research.

U.S. Environmental Protection Agency

The DOE continued informal interactions with the EPA on the rulemaking activities on a new public health and safety standard for Yucca Mountain. As was reported in Progress Report #14 (DOE, 1996b), and documented in the DOE recommendations transmitted to the EPA on March 29, 1996 (DOE, 1996d) DOE believes that the outcome of the standard is very

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critical to the future of geologic disposal in this country. Although the recommendations provided to the EPA are all important to developing a reasonable standard, the three issues thought to be the most important with respect to the ability to implement the standard in a licensing environment are as follows:

- The length of the regulatory time period
- The dose limits for individual and ground-water protection
- The location and characteristics of the critical population group.

These three issues have been the primary focus of discussion for some time now. In addition to its informal interactions with the EPA, the DOE has presented its views on these issues to the NRC staff, the Advisory Committee on Nuclear Waste, and the Nuclear Waste Technical Review Board. These and other related issues also have been discussed in various industry conferences, such as the International High-Level Radioactive Waste Management Conference in April/May 1996 and the Spectrum '96 Conference in August 1996.

Forecast: The DOE will continue to interact with the EPA throughout the rulemaking process. The next key step in this process is the interagency review of the draft rule that is coordinated by the Office of Management and Budget. Regular technical interactions and exchanges with the NRC will continue, as will meetings with the Advisory Committee on Nuclear Waste and Nuclear Waste Technical Review Board.

2.2.3.2 Issue Resolution

The DOE's approach to licensing and issue resolution has evolved from the process outlined in Section 8.1 of the SCP (DOE, 1988), which focused on resolving individual issues related to specific site characteristics. Issues were dealt with in relative isolation from one another and from an overall concept for the repository system. Experience gained in applying this process, however, indicates that the sufficiency of site characterization data and analyses can generally only be determined within the context of a coherent repository concept that includes both a design and an assessment of its performance in the geologic setting. The DOE believes that licensing success will depend in part on establishing such a conceptual framework and on focusing its near-term interactions with the NRC within the context of this framework.

The DOE is currently in the process of developing an overall repository concept to support the viability assessment and will communicate its progress to the NRC. The concept is expected to evolve over time as the design, site data, and performance analyses mature. As this conceptual framework develops, the DOE will seek to reach a common understanding with the NRC regarding the issues that are significant to the overall performance of a repository at Yucca Mountain. The DOE also will seek to reach agreement on the methodologies and approaches used to address important technical issues, such as criticality control and seismic design. A limited number of topical reports will be developed with the goal of receiving NRC safety

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evaluation reports that can be referenced in a license application as an appropriate means for resolving selected issues.

The goal of this new approach is to reach a mutual understanding of the developing repository concept that will provide a basis for the NRC's preliminary comments on the sufficiency of the DOE's site characterization analysis and design for inclusion in a license application. The revised approach is consistent with the intent of the issues-based approach that was described in the SCP. This approach also reflects the substantial change in the policy framework for repository development and the increased understanding of the Yucca Mountain site and repository design that have occurred since the SCP was written.

Activities conducted during the reporting period that relate to the evaluation of seismic hazards and repository criticality are summarized in the following sections. The status of actions related to open items from the NRC's Site Characterization Analysis (NRC, 1989) is also discussed.

Seismic Hazards

Seismic hazards issue resolution activities are focused on three DOE topical reports that describe the proposed seismic hazard assessment and seismic design methodologies for Yucca Mountain. Seismic Topical Report I (DOE, 1994b) describes the probabilistic seismic hazard assessment methodology for the potential repository. Seismic Topical Report II (DOE, 1995b) describes the seismic design methodology for systems, structures, and components at Yucca Mountain. Seismic Topical Report III, tentatively scheduled for 1998, will provide the seismic design inputs (seismic response spectra, time histories, fault displacement level, etc.) for the appropriate seismic hazard levels. This report may not be developed if the information can be supplied to the NRC in another format. Work this period focused on revising Seismic Topical Report II in response to the NRC staff's comments.

Although the DOE transmitted Seismic Topical Report I to the NRC on June 30, 1994, the NRC initially did not accept the report for detailed review. After further discussions and the submittal of supplemental information between October 1994 and March 1995, the NRC informed the DOE by letter dated September 22, 1995 (NRC, 1995b) that this report was accepted for detailed NRC review. The letter also provided four specific comments on the report to DOE, supported by several basis points. The DOE responded to the comments on January 29, 1996 (DOE, 1996e). By a letter dated July 25, 1996 (NRC, 1996b), the NRC informed the DOE that sufficient information exists in various forms to close all comments on Seismic Topical Report I. The DOE plans to make agreed upon changes to the report and to issue it as final early in FY 1997.

Seismic Topical Report II, Rev. 0, was completed by the DOE in October 1995 and was transmitted to the NRC on October 31, 1995 (DOE, 1995c). The report adapted the DOE seismic design approach based on performance goals for application to a geologic repository at Yucca Mountain. The report also addressed the seismic design of underground openings and ground support system and described the DOE design approach for fault displacement hazards. On

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March 13-14, 1996, NRC staff and their consultants met with DOE staff and contractors for an Appendix 7 meeting to discuss their preliminary comments and questions before formally transmitting any questions and comments to the DOE. A follow-on Appendix 7 meeting was held on April 23, 1996, to discuss items not covered in the first meeting. By a letter dated May 21, 1996 (NRC, 1996a), the NRC formally transmitted its review comments on Seismic Topical Report II.

As a result of the Appendix 7 interactions and in response to NRC staff comments, the DOE decided to drop its performance-goal based approach to preclosure seismic design and, instead, adopt an approach that incorporates pending requirements in the NRC's proposed rulemaking (60 FR 15180) for 10 CFR Part 60, including the requirement to identify and design for Category-1 and Category-2 design basis events. The DOE is revising Seismic Topical Report II to reflect this change and plans to submit Revision 1 of Seismic Topical Report II to the NRC early in FY 1997.

The DOE plans to implement its probabilistic seismic hazard analysis of the Yucca Mountain site during FY 1997. This analysis will be conducted using the methodology described in Seismic Topical Report I. The DOE also plans in FY 1997 to start developing the vibratory ground motion and fault displacement inputs appropriate for the preclosure seismic design of repository facilities, using the methodology described in Seismic Topical Report II. These design inputs are scheduled for completion early in FY 1998 and will be documented in a design study report. The DOE is still considering whether to submit this design study report to the NRC staff for informal review or to prepare a third seismic topical report for formal NRC staff review and comment.

Repository Criticality

The disposal criticality issue involves demonstrating that criticality control will be maintained in the repository such that 10 CFR Part 60 criticality requirements and repository performance objectives will be met. Fissile material remains in spent nuclear fuel after discharge from a reactor, and much of that material is very long-lived. Though this material gradually decays to nonfissile materials, additional fissile materials resulting from the decay of some nonfissile materials are created after the spent fuel is emplaced in the repository. Therefore, disposal criticality analysis is required for the period from the time of emplacement to thousands of years in the future.

The Project's approach to dealing with the issue of disposal criticality involves a risk-based criticality analysis methodology that will be used to demonstrate that potential criticality events during the postclosure period will not pose an unacceptable risk to the health and safety of the public. This approach is consistent with the 1995 recommendations of the National Academy of Sciences for Yucca Mountain standards (NAS, 1995).

The Project will also seek NRC approval of accounting for the reduced reactivity associated with spent nuclear fuel as compared with unirradiated fuel of the same initial enrichment. This approach is known as burnup credit. Additional possible criticality control

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methods are also being considered, including the addition of supplemental neutron-absorbing materials and/or moderator-displacing materials to the waste package.

Resolution of disposal criticality issues will be based primarily on the Disposal Criticality Analysis Methodology Topical Report, which is planned for submittal to the NRC in 1998. This topical report will seek NRC acceptance of the DOE's proposed criticality analysis methodology and its method for obtaining burnup credit.

During this reporting period, the DOE completed the Disposal Criticality Analysis Methodology Technical Report (CRWMS M&O, 1996c) and sent the report to the NRC to inform the NRC staff. This report provides a preliminary description of the DOE's proposed risk-based disposal criticality analysis methodology. It will be used as the basis for development of the Disposal Criticality Analysis Methodology Topical Report.

The DOE reiterated, in an April 12, 1996 letter to the NRC (DOE, 1996f), its concern about the wording of the existing NRC rule for disposal criticality control, 10 CFR 60.131(b)(7). The DOE believes that the rule does not clearly support use of the risk-based disposal criticality analysis methodology that the DOE believes is essential to demonstrating that the health and safety of the public will be protected against postulated postclosure criticality events.

Forecast: A DOE-NRC technical exchange has been scheduled for the next reporting period to discuss the Disposal Criticality Analysis Methodology Technical Report. This meeting is intended to support early communication and resolution of concerns the NRC staff may have on the DOE's proposed methodology for disposal criticality analysis. During the next reporting period, the DOE will continue to develop the disposal criticality analysis methodology and its supporting models. This effort is planned to lead to a revision to the Disposal Criticality Analysis Methodology Technical Report, scheduled for completion in late FY 1997.

Resolution of Site Characterization Analysis Open Items

The NRC has agreed to the closure of Site Characterization Analysis (NRC, 1989) Comment 42 (NRC, 1996c); closure of Comments 101, 103, and 115 but has disagreed with the closure of Comments 95 and 105 (NRC, 1996d).

At the end of this reporting period, 95 Site Characterization Analysis open items have been closed by the NRC (including 2 objections), and 103 items remain open. Most of the remaining open items await data to be acquired through site characterization activities for resolution. Of the remaining 103 Site Characterization Analysis open items, 33 are currently being reviewed by the NRC staff.

Supplemental responses to Site Characterization Analysis Comments 33, 55, and 130 were forwarded to the NRC during September 1996 (DOE, 1996g; DOE, 1996h; DOE, 1996i).

Appendix E provides the status of Site Characterization Analysis comment resolution, identifying actions that need to be performed to close the item.

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Forecast: The Project will continue discussions with NRC to address questions and concerns that may result from the staff's continued review of Seismic Topical Reports I and II.

The Project will provide a detailed response to the NRC's comment on the volcanism discussion contained in Progress Report #11 related to the potential impacts of ash falls on preclosure operations of the planned repository (NRC, 1995c).

Activities related to disposal criticality during the next reporting period will be focused on further development of the Disposal Criticality Analysis Methodology Topical Report and on continuing discussions with the NRC regarding the criticality rule in 10 CFR 60.131(b)(7).

Site Characterization Analysis open items will continue to be resolved as the site characterization and other programmatic activities provide pertinent data.

2.2.3.3 License Application Annotated Outline

The intent of the License Application Annotated Outline process was to support the development of the repository license application and to facilitate early resolution of issues regarding sufficiency of information provided in the license application. The process entailed producing a series of annotated outline versions for the license application.

Further development of this document was deferred indefinitely in September 1995 following development of the draft Revision 1 of the License Application Annotated Outline, because of Program redirection requested by Congress and funding constraints.

Forecast: No further revisions to the License Application Annotated Outline are planned. Information available in the draft Revision 1 of the License Application Annotated Outline will be used as appropriate in future Program documents. The structure of the annotated outline, which is based on NRC guidance for license application format and content, will also be available for use in developing the repository license application, if the site is found suitable.

Because there are no plans to further develop the License Application Annotated Outline, this subsection (2.2.3.3) of future progress reports will be titled "License Application" and will report progress in planning for and development of that document. Development of the license application plan, which will guide the development of the license application, is scheduled to begin during the next reporting period and to be complete by the end of FY 1997.

2.3 QUALITY ASSURANCE

The DOE is continuing to monitor the status and adequacy of the OCRWM QA Program. In addition, the DOE continues to refine QA Program enhancements (for example, consolidation of corrective action and nonconformance programs and certain verification functions) developed and implemented during the two previous report periods.

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2.3.1 Program Activity

Work continues on revising the QA Program implementing procedures to fully implement Revision 5 of the Quality Assurance Requirements and Description document (DOE, 1995d). This document is the principal QA requirements document of the Civilian Radioactive Waste Management Program and contains regulatory requirements and program commitments necessary for an effective QA program. Revision 5 of this document was issued on October 31, 1995.

The DOE continues to conduct a program of scheduled internal audits and surveillances of organizations supporting the Civilian Radioactive Waste Management Program. Results of audits and surveillances conducted during this reporting period indicate that the OCRWM QA Program was in compliance with requirements, effectively implemented, and satisfactory overall. In addition, the Office of Quality Assurance continues to manage and perform supplier audits and qualification surveys for the OCRWM QA Program.

Results of verification activities (i.e., surveillances) performed by QA Divisions of organizations supporting the DOE performed during this reporting period also indicated satisfactory overall Program implementation.

Forecast: The DOE will continue to perform OCRWM verification activities and, through an ongoing effort, will evaluate Program processes and functions to identify potential candidates for programmatic consolidation and integration.

2.3.2 Determination of Importance Evaluations

The DOE is responsible for performing determination of importance evaluations, which remain the mechanism established by the Project to evaluate proposed field activities with respect to their potential for adverse impact to Q-List items or site characterization testing. Because the natural barriers are included in the Q-List, each determination of importance evaluation essentially comprises both a waste isolation evaluation and a test interference evaluation for the proposed activity. Where a reasonable potential for adverse impact is identified, the evaluation establishes appropriate QA controls for the activity to prevent or limit the adverse impact. These controls then are transcribed into the applicable documents for implementing the activity (e.g., field work packages, design packages, specifications, and drawings).

The implementing line procedure, which controls the determination of importance evaluation, requires that every determination of importance evaluation be reviewed annually to determine whether critical inputs or assumptions have changed enough that the conclusions of the determination of importance evaluations may no longer be valid. During the reporting period, seven determination of importance evaluations were reviewed. No significant changes were identified in either critical inputs or assumptions for the reviewed determination of

importance evaluations. Various minor changes were recommended to improve consistency and to update references.

Thirty-six tracers, fluids, and materials reports from four responsible organizations were reviewed before inclusion in the tracers, fluids, and materials data base. A list of determination of importance evaluations performed during this reporting period is provided in Appendix F.

Forecast: Substantial determination of importance evaluation development work is scheduled for the next reporting period, predominantly in support of the south ramp and pad for tunnel boring machine holeout, ESF testing, and surface-based testing.

2.3.3 Q-List and Management Control List/Design Basis Event Analysis

The Mined Geologic Disposal System Q-List (DOE, 1994c) and Management Control List (DOE, 1994d) delineate permanent items (i.e., items that may become part of a licensed pre- or postclosure repository). The Q-List includes those permanent items determined to be important to radiological safety, important to waste isolation, or otherwise subject to the requirements of the Quality Assurance Requirements and Description document. The Management Control List includes those permanent items determined not to be subject to those requirements; they are instead subject to conventional quality management and design controls.

Both documents reflect the conclusions of classification analyses. The Q-List also contains items originally placed on it by "direct inclusion," which is a conservative approach initiated when the document was first issued. Such items can be removed only through documented analysis.

Classification Analyses support an Implementing Line Procedure that identifies whether a permanent item has a function that falls within one of the following seven categories (order does not imply relative importance):

- QA-1 Important to Radiological Safety
- QA-2 Important to Waste Isolation
- QA-3 Important to Radioactive Waste Control
- QA-4 Important to Fire Protection (i.e., of QA-1 or -2 items)
- QA-5 Important to Potential Interaction (i.e., function not required, but failure could impact QA-1 or -2 items)
- QA-6 Important to Physical Protection of Facility and Materials
- QA-7 Important to Occupational Radiological Exposure.

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Revisions to the classification analyses for the starter tunnel and south portal headwall, the ground support systems, and the main access openings were prepared during the reporting period. These revisions supported the evaluation of the south portal design activities and continued monitoring and adjustments in graded requirements. Conclusions for the new scope in these evaluations are consistent with similar evaluations performed previously.

The Yucca Mountain Q-List was revised to include the classification analysis revisions and to incorporate the Management Control List.

Forecast: Design basis event analyses will be defined and coordinated to evaluate repository design basis events to support repository and waste package designs and to support the establishment of QA classifications for repository items important to radiological safety or waste isolation. A full scope revision to the Q-List is also planned to reflect the current repository design, as defined in the MGDS Advanced Conceptual Design Report. Where formal classification analyses have not yet been performed, preliminary classification results (including bases) will be included and will be tracked appropriately in accordance with established procedures.

2.3.4 Design Control

Design control is concerned with the ESF requirements hierarchy, requirements flowdown, and traceability of the requirements to 10 CFR Part 60 regulations.

Background

In October 1994, the NRC documented continued concerns with the design control process, as implemented by the M&O, and with the DOE oversight of the M&O QA program. Their primary concerns were that the M&O had not demonstrated effective implementation of its QA program for design control and that the DOE had not provided effective oversight that promptly identified and corrected deficiencies at an early stage.

The DOE acknowledged that the NRC had raised valid concerns related to design control and that some problems were recurring. Extensive remedial actions were taken to ensure that all design products released for construction had incorporated appropriate requirements. Some of the difficulty related to the problem of tracing how 10 CFR Part 60 requirements flowdown through the Project document hierarchy to the design products. Thus, DOE committed to compiling these considerations into a single document that describes (a) the criteria used to identify and minimize potential impacts and (b) the incorporation of 10 CFR Part 60 requirements into the ESF design.

In March 1995, the Project developed and submitted the Regulatory Compliance Review Report (DOE, 1995e) to address NRC concerns, and in August 1995, supplemented that report (DOE, 1995f). Combined, the two reports demonstrated the allocation and traceability of the applicable 10 CFR Part 60 requirements into the design solutions for the configuration items

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included in ESF Design Package 2C. (Design Package 2C addresses north ramp excavation layouts, ground support, utilities, electrical power, site lighting, site grounding, and alcoves.) The evaluation found no examples of missed allocations, and also found that the appropriate 10 CFR Part 60 requirements have been conservatively allocated to ESF Design Package 2C.

In March 1995, NRC outlined a plan for a three-phase in-field verification of DOE's corrective actions addressing deficiencies in design control and DOE oversight of the M&O QA program (NRC, 1995d). Phases 1 and 2 were subsequently completed. Three recommendations resulted from the Phase 2 in-field verification: (1) expand rock bolt analysis, (2) clarify the reportable geologic conditions and procedures, and (3) re-evaluate the quality classification of pre-cast concrete inverts used in the ESF. The first two were resolved during the in-field verification. Later, a review of the third indicated that the Project should consider making the inverts a QA item, and such changes are being considered.

The NRC indicated it will follow up on its three recommendations during its Phase-3 verification.

Within the scope of the Phase 2 activities, the NRC found that DOE compliance with commitments was satisfactory. The NRC reported that open items were reduced in scope based on the results of the in-field verification.

Progress this Reporting Period

In a December 14, 1995, letter (NRC, 1995a), the NRC transmitted the results of its review of the DOE evaluation of the applicable 10 CFR Part 60 requirements into the design solutions for the configuration items included in ESF Design Package 2C. The NRC found that applicable requirements had been allocated appropriately to the ESF Design Package 2C. In this letter, the NRC also requested examples of design products that were developed and completed under the improved design process and examples of revised design requirements documents for their review. This information was needed before the design control issue could be closed. With respect to the flowdown of the 10 CFR Part 60 requirements, however, the NRC staff identified a few instances in which it disagreed with DOE's interpretation of the requirements. In a letter dated September 25, 1996 (DOE, 1996i), DOE transmitted responses to the NRC staff's comments and provided information requested in the referenced December 14, 1995, letter. The DOE's response letter addressed DOE's interpretation for applicability of each of the 10 CFR Part 60 requirements. The responses were organized into two groups. Group 1 addressed those 10 CFR Part 60 requirements in which the NRC staff commented on the DOE's interpretation of the 10 CFR Part 60 requirements provided in the Regulatory Compliance Review Report. Group 2 addressed those 10 CFR Part 60 requirements in which the DOE's interpretation, application, or both has been updated from the position presented in the Regulatory Compliance Review Report. Also, an example design package (the Topopah Spring (TS) South Ramp Excavation Layout) developed under the latest revision of the design procedures was transmitted to the NRC. The sample design package consisted of four Topopah Spring south ramp excavation layout drawings and supporting design analysis, and the applicable QA classification

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analysis for this design package. In addition, copies of Revision 2 of the ESF Design Requirements, which has been approved for design applications, were transmitted to the NRC.

Another item addressed by the Project as part of the September 25, 1996 response letter was a DOE commitment to revise the Regulatory Compliance Review Report for each major design package as required to provide continuing assurance that impacts are adequately addressed. This commitment was written at a time when the design of the ESF was divided into packages, and the ESF Design Requirements did not clearly indicate how the ESF design complied with the 10 CFR Part 60 requirements. The package concept is no longer being used for the ESF design. The design organization now releases individual parts (e.g., south portal, extension of conveyor, extension of ground support) of the design. The revised ESF Design Requirements, which clearly indicates how the 10 CFR Part 60 requirements identified by NUREG-1439 ("Staff Technical Position on Regulatory Considerations in the Design and Construction of the Exploratory Shaft Facility") are addressed, meets the intent of DOE's commitment to update the Regulatory Compliance Review Report. Therefore, the basis for that concern no longer exists, and the commitment has been satisfied and considered closed.

Furthermore, the September 25, 1996 DOE letter either addressed or closed several other open items or NRC comments. These included the Site Characterization Analysis open item 130, and the NRC staff recommendations that resulted from the NRC in-field verification conducted April 3-6, 1995. Open item 130 deals with the NRC concern that the DOE design acceptability analysis addressed only 22 of the 52 requirements of 10 CFR Part 60 considered applicable to the ESF and that the other 30 requirements also need to be addressed. On the basis of information and responses covering all 10 CFR Part 60 requirements, as provided in the DOE's September 25, 1996 response letter, DOE believes that open item 130 has been adequately addressed and may be closed. Also, DOE has taken action to address the NRC staff recommendations that resulted from the in-field verification conducted on April 3-6, 1995. These recommendations were for DOE to (a) expand numerical modeling of rock bolts to include all pertinent types and applications, (b) clarify Administrative Procedure 6.14 regarding reportable geologic conditions, and (c) re-evaluate the quality classification of pre-cast concrete inverts. DOE believes that its actions and evaluations have adequately addressed these recommendations.

Forecast: The Phase 3 in-field verification, originally expected to be conducted in FY 1996, has not been announced by the NRC during this reporting period. Work will continue on assessing the Project's design process to identify actions that will improve the DOE's ability to independently evaluate design products for compliance with 10 CFR Part 60.

2.4 PROGRAM OUTREACH

The objective of Program Outreach is to ensure open and informative interactions with the public and Project stakeholders in accordance with the Nuclear Waste Policy Act of 1982 and the Secretary of Energy's stakeholder policy. To comply with these requirements, the Project conducts interactions with the State of Nevada, the public and public interest groups, the Nevada

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business community, affected counties, local government agencies, the legislature, and the media. The approach to these interactions can be broken into three areas of emphasis: stakeholder involvement, public outreach programs, and product development. The following are means by which the Project interacted with and provided information to the public and Project stakeholders.

During this reporting period, 101 tours of Yucca Mountain, including three Public Open House tours, were conducted for 1372 members of the public and other interested parties. Tours of special interest included tours for guests from the National Conference of State Legislatures; guests from the International High-Level Radioactive Waste Management Conference; guests from Historically Black Colleges and Universities; Nuclear Energy Institute tours for various groups; and congressional staff members.

Numerous programmatic and technical workshops, presentations, and meetings were held in various Nevada communities to provide current information to the public regarding site characterization progress. The staff held individual meetings with officials of the Affected Units of Government to discuss Project issues and to provide updates of Project activities. Project Manager Wesley Barnes gave Project updates to the National Conference of State Legislatures and the Nevada Legislative Committee on High-Level Radioactive Waste. A total audience of approximately 5100 people attended 82 speaking presentations during this period, which included technical presentations, general Project overviews, and educational presentations.

The International High-Level Radioactive Waste Management Conference was held April 29 - May 3, 1996, in Las Vegas, Nevada. Project staff organized and chaired four sessions in the public affairs arena, helped create an OCRWM exhibit, and helped staff the exhibit.

Approximately 5900 individuals visited the Yucca Mountain Science Centers, located in Las Vegas, Beatty, and Pahrump, Nevada, during this period. As a cost saving measure in this activity, the Beatty Science Center was consolidated into one building with the Beatty distribution warehouse. At these centers, Project staff presented one Yucca Mountain Speaker Series lecture, two Discovery Days, two teacher workshops, eleven YMCA workshops, and seven environmental, energy, and geology workshops for fifth-graders. Other events under the Educational Program included a Neighborhood Dialogue in West Las Vegas where members of the community could ask questions of Project staff members, JASON Project, and a JASON mentoring program. The JASON Project, a unique partnership among governmental agencies, private industry, and the Clark County School District, allows students access to state-of-the-art technology. This year, students were transported via technologies to Everglades, Florida Bay, Florida Keys, coral reefs, and relic reefs in the Strait of Florida. Project staff also set up and staffed an exhibit at the White Pine County Fair to update the residents of White Pine on the status of the Project.

Project staff completed the August 1996 New Work Update video to inform the public and Project stakeholders about the scientific studies that have occurred at Yucca Mountain since the last update at the beginning of the year. Copies of this video were distributed to interested stakeholders and members of the news media. Project staff also completed a video, "Geologic

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Disposal of Nuclear Waste: Solving an Environmental Problem," and a two-hour compilation video that was compiled from eight individual videos, representing various aspects of the nuclear waste program, that can be used by general audiences.

The Yucca Mountain Site Characterization Project Home Page on the internet was accessed over 183,600 times this period by various national and international business, educational, and government entities.

The Project researched, created, revised, modified, and distributed a variety of public information products, responded to external information requests, and operated the Civilian Radioactive Waste Management Information Center Toll-free Number.

Forecast: Project interactions with public and Project stakeholders will continue as needed.

CHAPTER 3 - SITE PROGRAMS

INTRODUCTION

The Site Characterization Program consists of 13 scientific investigation programs comprising more than 100 studies. Through the studies, information about the natural features and processes of the Yucca Mountain site is collected, analyzed, and synthesized. This information is needed to determine whether the Yucca Mountain site is suitable for a repository and, if so, to support repository design and application for the license that would authorize construction of a repository. The information collected will be used to determine (a) whether a repository can be constructed and operated at the site while assuring the health and safety of the public, and (b) whether the waste emplaced in the repository will remain isolated from the biosphere for thousands of years.

Background

The original testing and analysis approach, as envisioned in the 1988 Site Characterization Plan (SCP) (DOE, 1988) was intended to identify and evaluate significant risks and uncertainties in scientific hypotheses before the license application was prepared and submitted. That testing and analysis program was based on the information requirements in the disposal regulations (10 CFR Part 60) and in the siting guidelines (10 CFR Part 960). The purpose of the SCP was to ensure that sufficient information would be collected to determine the suitability of the site, design a repository, assess the performance of the repository system, and develop an adequate license application for construction authorization. The SCP approach included the flexibility to modify the program as new data confirmed or refuted the importance of specific items of information (see, for example, p. 8-0-1 of DOE, 1988).

Progress in surface and subsurface investigations, especially over the last four years, has allowed the scope of site characterization to be reduced. Observations of the natural system and site data collected since 1978 have allowed many site conditions to be characterized, conceptual models to be advanced, and uncertainties to be bounded. Along with assessments of expected repository performance and continued development of a strategy to contain and isolate the waste, the U.S. Department of Energy (DOE), has used the results from site characterization activities to develop a Long-Range Plan (CRWMS M&O, 1996a) that narrows the scope of the testing and analysis program to focus on the relatively few remaining scientific and technical uncertainties that are important to the design and long-term performance of the potential repository. Recognizing the changes and the need for traceability in the site characterization program, the DOE initiated an effort to document the changes to the program since the SCP was issued. Summary information at the investigation level (i.e., 8.3.1.x.x) is included in Appendix A of this progress report.

Data from Project Staff will provide the technical basis for the viability assessment, the suitability determination and Secretarial recommendation, and the license application. By the end of fiscal year (FY) 1998, Project Staff expects to provide sufficient information regarding the

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outstanding technical questions about the characteristics of the site and the expected performance of the repository system to support the viability assessment.

Interrelationships with Other Program Elements

The site investigations program is designed to provide information on the geologic, hydrologic, geomechanical, geochemical, climatological, and meteorological characteristics of the site. Information is gathered using a variety of field and laboratory studies. The information collected under the site investigations program will provide the basis for the site viability assessment and also will be used by other Program elements to support Mined Geologic Disposal System (MGDS) design, performance assessment, and licensing.

Systems engineering determines various requirements to ensure that (a) site characterization activities do not compromise the design and construction of the MGDS and (b) that construction activities do not compromise site characterization activities. Information on the three-dimensional structural and stratigraphic characteristics of the potential repository block is needed for repository design. In particular, faults will affect repository layout, and tectonics studies are needed to establish seismic design parameters. Likewise, site characterization provides information needed to construct the Exploratory Studies Facility (ESF) and establish controls needed to prevent potential interference between tests. Design organizations identify information needs related to ESF and repository design, and establish controls to prevent potential interference between construction and tests. Particularly important items of information for design and construction are geotechnical properties of the rock and seismic hazard assessments.

Site characterization activities provide information vital to waste package design and material selection, including information on climatology; infiltration; the unsaturated zone, including bounds on infiltration and percolation flux rates and water chemistry. The site investigations program also provides data on the effects of heat on the physical behavior of rock, on the chemical composition of the water, on matrix and fracture flow in the potential host rock for consideration in waste package design, and on relative humidity. Design issues pertaining to percolation flux and relative humidity are discussed in Chapter 5 of this progress report. Performance assessment issues pertaining to percolation flux and relative humidity are discussed in Chapter 6 of this progress report.

Significant Results During this Reporting Period

During the reporting period, several studies produced results significant to the description and evaluation of the site. Generally, the results apply to studies in two broadly defined disciplines: (1) surface geology, site tectonics and geophysics, and natural resources, and (2) climate, ground-water flow, geochemistry, and radionuclide transport.

Continued interpretation of regional surface geophysical data indicate that a broad structural depression exists beneath Crater Flat and Yucca Mountain. The Bare Mountain fault forms the western boundary of the feature. Smaller faults identified in seismic reflection data

generally correspond with faults mapped at the surface. Data from intermediate-scale seismic lines show that some faults offset the Paleozoic-Tertiary contact beneath Yucca Mountain and Crater Flat. Hence, the contact appears to be an unconformity and could not represent an active shallow detachment surface.

At Yucca Mountain, detailed geologic mapping within the Paintbrush Group has shown that the central block of Yucca Mountain is a structural mass of Tertiary volcanic rocks bounded on the west by the Solitario Canyon fault and on the east by the Bow Ridge fault. The main phase of fault movement occurred in the mid-Miocene and is bracketed between 12.7 and 11.6 Ma. Slip rate estimates are low and appear to have been relatively constant over a span of 500,000 to 1,000,000 years. These slip rates are considered to represent a low level of activity, particularly when compared to slip rates that are one to two orders of magnitude higher along some of the strike-slip faults elsewhere in the region.

The results of the Probabilistic Volcanic Hazard Analysis show that the expected annual frequency of intersection of the potential repository by a volcanic event is about 1.5×10^{-8} —so small that there is a very small probability of disruption of the repository by a volcanic event during the next 10,000 years.

No perched water body has been intersected by the ESF nor has any perched water been found dripping or draining into the ESF. Studies are under way to determine whether the apparent absence of perched water may be the result of removal of water by ventilation needed during ESF excavation and construction.

The three-dimensional site-scale model of the unsaturated zone has been updated. The model now represents most, if not all, important processes and components of the mountain, including faults and fault offsets, perched water in appropriate locations, rock matrix and fracture properties, observed temperature profiles, and fast flow paths. Previous modeling of the unsaturated zone assumed infiltration and percolation flux rates on the order of 0.1 mm per year. Results during this reporting period indicate that average shallow infiltration over the 230-square-kilometer study area around Yucca Mountain may be about 11.6 mm per year. Exercise of unsaturated zone models utilized estimates of net infiltration 4.5 mm per year over the study area around Yucca Mountain, and 4.4 mm per year over the potential repository area. These values are appropriate to the respective model domains; the difference between the values used for model boundary conditions resulted from differences in the areas over which the estimates were calculated.

Analysis of available temperature and heat flow data indicate that the average percolation flux in the repository area may also be on the order of 5 mm per year, which is significantly higher than estimates used in previous modeling. It should be recognized, however, that at least two mechanisms are capable of reducing percolation flux (e.g., lateral diversion and vapor exhaust). Results of the analysis of lateral flow using the unsaturated zone model indicate that lateral flow within the Paintbrush nonwelded (PTn) hydrogeologic unit is most prevalent at low percolation flux rates, but the actual magnitudes of such fluxes are not yet known. Similarly, barometric pumping is known to be capable of removing water vapor from the unsaturated zone,

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but the magnitude of this effect has not yet been quantified. The effects of higher net infiltration rates and vapor movement on dryout of the potential repository, and the effects of higher percolation flux on lateral flow in the PTn, could have impacts on the ability to maintain a dry repository and on repository system performance. For example, simulation studies indicate that doubling the precipitation could increase the rate of net infiltration by five to seven times. These components of the overall water balance and their potential impacts on flow and transport modeling, and repository performance are being evaluated.

Results of air permeability studies indicate that the Topopah Spring welded (TSw) is anisotropic with a vertical-to-horizontal permeability ratio of about 10:1. Pneumatic pressure records indicate that pressure signals are transmitted nearly instantaneously throughout the entire Topopah Spring section, indicating that the fractures within the Topopah Spring Tuff are very permeable and highly interconnected within both the lithophysal and nonlithophysal subunits. Likewise, shut-in pressure monitoring of a borehole in the Bow Ridge Fault Alcove indicate that the Tiva Canyon welded hydrogeologic units is highly permeable. Gaseous-phase carbon-14 in the Topopah Spring Tuff was determined to be considerably older than aqueous-phase carbon-14 in the underlying Calico Hills Formation. This relationship indicates that rapid fracture flow may be the dominant aqueous transport mechanism, whereas diffusion seems to dominate the gaseous-phase system. Alternatively, the relatively young water in the Calico Hills Formation may be the result of lateral flow from the vicinity of Solitario Canyon.

Gas and liquid flow within the welded tuffs of the unsaturated zone occur primarily through fractures, and chlorine-36 data from the ESF indicate that at least some water has penetrated to repository depths in the last 50 years. Deep percolation occurs as episodic pulses of inflow that propagate rapidly downward along fractures and bypass much of the rock matrix. Within the Paintbrush Tuff nonwelded (PTn) hydrogeologic unit, evidence of extensive lateral flow is lacking, and interception and diversion of flow downward along structural pathways does not appear to be significant. However, lateral flow above the low permeability zeolitic rocks in the Calico Hills Formation and the Prow Pass Tuff has been observed in simulations.

Data from fractured tuff column experiments indicate fracture flow does not always result in fast pathways for actinide migration along fractures. Hence, calculations that incorporate simple fast pathway assumptions may lead to unnecessarily conservative predictions of radionuclide releases to the accessible environment.

Studies of zeolite stability indicate that clinoptilolite beneath the repository is expected to provide sorptive capacity to retard radionuclides that may be released from the repository. While the affinity of uranium for Yucca Mountain tuffs is generally low, the highest sorption coefficients for uranium have been obtained for zeolitic tuffs, but uranium sorption appears to be controlled by pH, alkalinity, and alkaline-earth ion concentrations. Batch sorption studies of neptunium transport show that Np(IV) sorbs well onto calcite and calcite-rich tuffs under oxidizing conditions. This result indicates that Np(IV) may be significantly retarded under fracture-flow conditions because of the calcite that commonly coats fractures. Studies of plutonium retardation indicate that reduction-oxidation potential is the most important ground water compositional parameter for determining the transport behavior of plutonium.

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Data on solubility limits show that uranium, thorium, neptunium, plutonium, and americium have low solubilities in Yucca Mountain waters. Comparisons of the predicted uptake of sorbing radionuclides by the tuff with collected data indicate that predicting diffusion using batch sorption coefficients should result in conservative estimates.

Data from many thousands of measurements in the Paintbrush Group (which includes the host rock for the potential repository) lead to the conclusion that fracture intensity and network connectivity are much greater in the welded tuffs than in the nonwelded or poorly welded units. Fracture connectivity is an important factor in the hydrologic modeling of fluid flow within the potential repository.

Data from various climate and hydrology studies are converging, and a major conclusion based on terrestrial and aquatic records of past climates, and other data, is that much higher levels of effective moisture existed during most of the Pleistocene compared with the present time.

Altered zone geochemical simulations indicate that significant porosity changes are possible in the condensation zone above the repository. Additional work is necessary to assess the potential impacts of the possible changes in porosity.

Preliminary data from the single heater testing indicated that most of the sensors were operating properly. The exceptions were the geochemical (ion-specific) sensors which have not operated properly since installation. The test will measure the thermal effects on rock and provide an opportunity to test the instruments before the larger and more complex drift scale tests are conducted.

Significant progress was made toward synthesizing data from the various site programs and identifying and prioritizing remaining open technical issues. Synthesis reports provide data for (a) characterizing the site, (b) design work on key elements of the repository and waste package, (c) the development, refinement, and validation of process models, and (d) the development of total system performance assessment models. The synthesis reports represent important milestones for the Yucca Mountain Site Characterization Project (Project) because of the tangible evidence provided that site programs have matured and are being closed out. Planning benefits derived from the development of the synthesis reports included identification of additional or outstanding data needs, assistance in the determination of information collection priorities, and clear indications that some resources can be reallocated. Synthesis reports have been completed for mineralogy and petrology studies, radionuclide retardation studies, climate studies, unsaturated zone infiltration, unsaturated zone matrix hydrologic properties, gaseous-phase circulation in the unsaturated zone, preclosure tectonics, and characteristics of fractures (for the postclosure rock characteristics program).

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Overview

Table 3-1 lists the 13 scientific programs, and one study that was added after the SCP was issued, that now comprise the site characterization effort at Yucca Mountain, Nevada. This table also lists the progress report section number for each program, briefly describes the scope of each program, and references the corresponding section of the SCP.

These programs are discussed in detail in the progress report sections listed in Table 3-1. The discussions in these sections reflect the impact of consolidating study plan work scopes on the individual studies and activities of the SCP. The discussions contain many references to study plans, identify SCP sections for which study plans have not been written, and explain why specific study plans may not be developed. Explanations may include work scope that has been transferred or aggregated into other study plans; work that has been completed and reported; or work for which no study is necessary because data are available from other sources. The status of the study plans are summarized in Appendix G.

Four figures and one additional table have been included to help the reader understand the information presented in this chapter. These figures and the table are referenced in many of the study descriptions.

- Figure 3-1 is a regional location map showing surface features in the Yucca Mountain vicinity.
- Figure 3-2 shows the locations of the proposed repository blocks and of boreholes in the potential repository area.
- Figure 3-3 shows locations of selected geologic and potential repository features related to significant results during the reporting period.
- Figure 3-4 shows the ESF and test alcoves and presents a summary of the remaining test activities for each alcove.
- Table 3-2 shows the stratigraphy of Yucca Mountain as determined for various usage classifications.

Additional tables that present data specific to particular studies have also been included where appropriate, but these data tables are not widely referenced or cited repeatedly in the descriptions in this chapter.

See the references section (Appendix L) for information about compilation of figures required by Federal Executive Order 12906 (59 FR 71, p. 17671-17674).

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Table 3-1. Descriptions and Site Characterization Plan Sections (in parentheses)
for Site Programs Described in Chapter 3

3.1 Geohydrology	Investigates surface and subsurface hydrology on both site and regional scales, with ground-water flow system characterization and modeling for both the unsaturated zone and saturated zone (SCP Section 8.3.1.2)
3.2 Geochemistry	Investigates and models rock chemistry and mineralogy, ground-water chemistry, and geochemical behavior of materials along potential radionuclide transport pathways (SCP Section 8.3.1.3)
3.3 Rock Characteristics	Characterizes and models rock stratigraphic and structural features and distributions within the site area, and integrates geophysical and drilling activities to obtain subsurface stratigraphic and structural data (SCP Section 8.3.1.4)
3.4 Climate	Analyzes paleoclimate, paleohydrology, and paleoenvironment, and characterizes modern climate, future climate, and future hydrology (SCP Section 8.3.1.5)
3.5 Erosion	Characterizes modern and past erosion and evaluates the potential effects of future climate and tectonics on erosion (SCP Section 8.3.1.6)
3.6 Postclosure Tectonics	Characterizes tectonic features, such as igneous activity and fault and fold deformation in the Yucca Mountain vicinity, with emphasis on volcanic activity, and analyzes the potential effects of tectonic processes on a potential repository and the site ground water system (SCP Section 8.3.1.8)
3.7 Human Interference	Evaluates the known and potential natural resources in the site area, and the potential for future human intrusion into the site area in search of such resources (SCP Section 8.3.1.9)
3.8 Meteorology	Characterizes the site and regional meteorological conditions of the Yucca Mountain vicinity (SCP Section 8.3.1.12)
3.9 Offsite Installations and Operations	Determines the presence, and potential impacts on the site area, of offsite industrial, transportation, and military installations and operations in the Yucca Mountain vicinity (SCP Section 8.3.1.13)
3.10 Surface Characteristics	Characterizes the topographic characteristics and properties of soil and rock in the site area (SCP Section 8.3.1.14)
3.11 Thermal and Mechanical Rock Characteristics	Determines rock thermal and mechanical properties from laboratory and in situ investigations and characterizes thermal and mechanical stress conditions at the site (SCP Section 8.3.1.15)

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Table 3-1. Descriptions and Site Characterization Plan Sections (in parentheses)
for Site Programs Described in Chapter 3 (continued)

3.12 Preclosure Hydrology	Characterizes the potential for flooding, determines the location of an adequate water supply for repository construction and operation, and characterizes preclosure hydrologic conditions in the unsaturated zone at Yucca Mountain (SCP Section 8.3.1.16)
3.13 Preclosure Tectonics	Characterizes faults, seismicity and tectonic stress field, and evaluates the potential for faulting, ground motion, and volcanic activity in the site vicinity during the previous period (SCP Section 8.3.1.17)
3.14 Altered Zone Characterization	A new activity that was not addressed in the SCP has been created to develop and validate techniques to analyze the performance of the natural system under potential changes resulting from waste emplacement (SCP Section - N/A [new study added after SCP issued])

Figure 3-1. Regional Location and Surface Features Map

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Figure 3-2. Map Showing Exploratory Studies Facility, Potential Repository Blocks, and Repository Area Boreholes

Figure 3-3. Map Showing Locations of Selected Site Features

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Figure 3-4. Map of Exploratory Studies Facility (ESF) Showing Names and Locations of Test Alcoves and Major Tests Planned for Each Alcove

Formal Geologic Stratigraphy (after Sawyer et al., 1994)		Hydrogeologic Units (Modified from Montazer and Wilson, 1984)	Thermal/Mechanical Units (Ortiz et al., 1985)
Qac		Alluvium	UO
Paintbrush Group	Tiva Canyon Tuff	Tiva Canyon Welded Unit TCw	TCw
	pre-Tiva Canyon bedded tuff	Paintbrush Nonwelded Unit PTn	PTn
	Yucca Mountain Tuff		
	pre-Yucca Mountain bedded tuff		
	Pah Canyon Tuff		
	pre-Pah Canyon bedded tuff		
	Topopah Spring Tuff	Topopah Spring Welded Unit TSw	TSw1
			TSw2
			TSw3
	pre-Topopah Spring bedded tuff	Calico Hills Nonwelded Unit CHn	CHn1v
	Calico Hills Formation		CHn1z
Crater Flat Group	Prow Pass Tuff	Crater Flat Unit CFu	CHn2z
	Bullfrog Tuff		CHn3z
	Tram Tuff		PPw
			CFun
			BFw
		CFMn	
		TRw	

*From Sawyer et al., 1994

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Table 3-2. Comparison of the Lithostratigraphic, Hydrogeologic and Thermomechanical Units of the Paintbrush Group, Calico Hills Formation, and Crater Flat Group Used at Yucca Mountain (Modified from CRWMS M&O, 1996f)

3.1 GEOHYDROLOGY (SCP SECTION 8.3.1.2)

The changes to the Geohydrology Program since the SCP was issued are summarized in Appendix A in Section A.1.1.

3.1.1 Study 8.3.1.2.1.1 - Characterization of the Meteorology for Regional Hydrology

The objectives of this study are (a) to characterize the area surrounding Yucca Mountain in terms of precipitation and its relationship to surface runoff, with particular emphasis on the Fortymile Wash drainage basin, and (b) to provide input into the rainfall-runoff model development effort.

About six years ago, the study was modified to emphasize meteorological information needed to develop an infiltration model for Yucca Mountain. At that time, precipitation runoff modeling was de-emphasized.

The FY 1995 work to obtain closing calibrations for field instruments continued as part of the preparation of the FY 1995 data package. The timing of 0.1 mm precipitation events, measured using the tipping-bucket gauges, was determined. All weather-station data were compiled into daily files and prepared for technical review.

Measurements of the timing, amount, intensity, and duration of precipitation continued using a diminished site-scale network of 14 tipping-bucket gauges. Virtually no precipitation occurred during this reporting period. In April, the two remaining weather stations were discontinued as a part of network consolidation after a joint review of the meteorological monitoring being conducted in support of Site Characterization Program hydrologic studies and Radiological and Environmental Field Programs.

Two reports were being prepared. The first report (Hevesi and Flint, in press) provides a distribution of recharge estimates for use in the Yucca Mountain regional saturated zone model and a methodology for estimating the spatial distribution of precipitation for input to the site-scale numerical infiltration model. The second report (Hevesi et al., in prep.) provides information regarding the El Niño weather pattern that is potentially important in the development and testing of future climate scenarios for site characterization and performance assessment models of Yucca Mountain.

Forecast: During the first quarter of FY 1997, operation of the 14 tipping-bucket precipitation gauges will be transitioned to Radiological and Environmental Field Programs to complete the consolidation of the site characterization and environmental meteorological networks. Analyses and interpretations of site and regional meteorological data will support the refinement of the numerical infiltration model developed under Activity 8.3.1.2.2.1.2, discussed in Section 3.1.5 of this progress report.

3.1.2 Study 8.3.1.2.1.2 - Characterization of Runoff and Streamflow

The objectives of this study are to (a) collect basic data on surface-water runoff at, and peripheral to, Yucca Mountain and on its hydrologic flow system; (b) use the streamflow data to describe the runoff characteristics of the area and to assess the response of runoff to precipitation; (c) assess the potential for flood hazards and related fluvial-debris hazards; and (d) provide basic data and interpretations of surface-water runoff to investigations that evaluate the amounts and processes of infiltration and ground-water recharge at Yucca Mountain and surrounding areas.

Note: Regional Hydrologic System Synthesis and Modeling is described under Study 8.3.1.2.1.4.

Activity 8.3.1.2.1.2.1 - Surface-water runoff monitoring. The objectives of this activity are (a) to develop needed basic data on the characteristics, magnitudes, frequencies, and timing of surface-water runoff to develop an understanding of the relation between specific runoff events and the characteristics of the storms and associated precipitation; and (b) to develop a streamflow data base adequate to provide the necessary calibration data for precipitation-runoff modeling efforts for the regional study area, and site-scale water-balance and infiltration modeling.

Monitoring continued at the three continuous-recording streamflow gauges on Fortymile Wash at the Narrows, Fortymile Wash near well UE-25 J#13, and Fortymile Wash near Amargosa Valley. Although several storms tracked through southern Nevada during the reporting period, no runoff was observed or reported at the three gauges or anywhere in the Yucca Mountain area. Monitoring of regional runoff and streamflow was de-emphasized at the end of water year 1995 (October 1, 1994, through September 30, 1995) by discontinuing 16 continuous-streamflow gauges and 22 peak-flow gauges. Data for Nevada Water Year 1995 is reported in Bauer et al. (1996).

Records of data collected during water year 1995 for 13 continuous-recording streamflow, 12 peak-flow, and 20 precipitation gauges were processed for publication in the U.S. Geological Survey (USGS) annual water-data report for Nevada. Computations of peak discharges for the runoff of March 11, 1995, were finalized and used to define or modify the stage-discharge relation at many of the streamflow gauges within the network.

Activity 8.3.1.2.1.2.2 - Transport of debris by severe runoff. The objective of this activity is to document, both quantitatively and qualitatively, the characteristics of debris transported by intense surface runoff.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Monitoring will continue at the three continuous-recording streamflow gauges on Fortymile Wash at the Narrows, Fortymile Wash near well UE-25 J#13, and Fortymile Wash near Amargosa Valley. Data records for water year 1996 will be reviewed and processed for publication in the annual water-data report for Nevada.

3.1.3 Study 8.3.1.2.1.3 - Characterization of the Regional Ground-Water Flow System

The objectives of this study are to further define the distribution of hydraulic properties of the regional ground-water flow system and to use hydrologic, hydrochemical, and heat-flow data to determine the magnitude and direction of ground-water flow.

Activity 8.3.1.2.1.3.1 - Assessment of regional hydrologic data needs in the saturated zone.

The objective of this activity is to prioritize data needs for use in the regional ground-water flow description.

A memorandum report was prepared (Luckey, 1996) updating the status of understanding of key data uncertainties. The memorandum identified two "key issues," which are items needed to meaningfully evaluate the contributions the saturated zone can make to meeting regulatory requirements. The key issues were: (a) resolution of the cause of the large hydraulic gradient, and (b) quantification of Fortymile Wash recharge. The memorandum also identified four "potential issues," which are items that could be important under a dose-based regulatory standard where doses are calculated at long distances from a repository after thousands of years. The potential issues were: (a) hydraulic data uncertainty, (b) role of faults in partitioning flow, (c) interaction between carbonate aquifer and volcanic aquifers, and (d) flow through the Timber Mountain area. The memorandum noted that a number of saturated zone issues have been resolved over the life of the Project. These include (a) accurately defining the potentiometric surface in the area of the small hydraulic gradient, (b) demonstrating that previously unexplained "water-level anomalies" were actually instrumentation problems, (c) determining that water-level fluctuations caused by seismic events would not threaten a repository, (d) accurately estimating ground-water discharge at Alkali Flat, and (e) substantially improving modeling of the regional flow system.

Activity 8.3.1.2.1.3.2 - Regional potentiometric-level distribution and hydrogeologic framework studies. The objectives of this activity are to determine the potentiometric distribution within the regional ground-water flow system, and to characterize the hydrogeologic framework of the regional ground-water flow system to support reliable estimates of ground-water flow direction and magnitude within the saturated zone.

A second single-well aquifer test was conducted in USW G-2 to gather data that may provide insights into the possible causes for the large hydraulic gradient located to the north of the potential repository. Although the test was conducted under Activity 8.3.1.2.3.1.2, this activity (8.3.1.2.1.3.2) is responsible for the work. Completion of the test has been deferred pending more complete recovery of the water level in the well following the pumping test. Beginning on April 8, 1996, the well was pumped at a rate of approximately 58 gpm (220 L/min). The test was originally scheduled for 10 days, but was extended 7 additional days at DOE direction. Cumulative discharge during the test was approximately 1.4 million gallons (5.3 million L) and the drawdown in the well at the end of the test was 124.45 ft (37.9 m). Data from the early part of the test closely matched data from the February test (see Activity 8.3.1.2.1.3.1 in Progress Report #14; DOE, 1996b). Recovery from the test has been slow with approximately 15 ft (4.6 m) of residual drawdown at the end of May and approximately 6 ft

(1.8 m) at the end of June. By the end of August, the well had not fully recovered and showed a residual drawdown of approximately 2 ft (0.6 m). Slow recovery also occurred during the February test.

Activity 8.3.1.2.1.3.3 - Fortymile Wash recharge study. The objective of this study is to determine to what extent (quantitatively, if feasible) Fortymile Wash has been a source of recharge to the saturated zone under present and past conditions.

Work continued on a report to document and analyze recharge in Fortymile Wash since the 1960s (Savard, in prep.). The report describes recharge resulting from streamflow that occurred during El Niño periods in 1969, 1983, 1992, 1993, and 1995 and confirms the influence of global weather patterns on Yucca Mountain hydrology. Long-term recharge in Fortymile Canyon (Fortymile Wash north of Yucca Mountain) from Pah Canyon to Yucca Wash was estimated to be 26000 m³/yr. Preliminary estimates of recharge from the more complex streamflow regimes in upper Jackass Flats, lower Jackass Flats, and the Amargosa Desert have been made and are in technical review. The report also examines the relationship between streamflow and El Niño in several small watersheds throughout the southwestern United States. El Niño effects were seen but not in all basins in all years.

A report documenting precipitation, streamflow, unsaturated zone, and saturated zone data for Fortymile Wash during water years 1993-94 (Savard, 1996) was issued in June 1996.

Minimal water-level data were collected during this period because other data collection activities were not funded. Based on the absence of major storm events during the reporting period, as indicated by meteorological and stream flow monitoring, it is likely that no runoff events occurred that could have caused ground water recharge.

Activity 8.3.1.2.1.3.4 - Evapotranspiration studies. The objective of this activity is to improve estimates of ground-water discharge by evapotranspiration in the Amargosa Desert to provide boundary-condition data for regional ground-water flow models.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Further analysis will consider the more complete recovery, as well as additional hydrogeologic models to resolve results from different test and recovery periods. The report on historical Fortymile Wash recharge will be completed.

3.1.4 Study 8.3.1.2.1.4 - Regional Hydrologic System Synthesis and Modeling

The objectives of this study are to synthesize the available data into a model and make a qualitative analysis of how the system is functioning, and to represent quantitative observations of hydrogeologic data pertaining to the ground-water flow system in a comprehensive numerical model of ground-water flow.

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Activity 8.3.1.2.1.4.1 - Conceptualization of regional hydrologic flow models. The objectives of this activity are to synthesize available data into a conceptual model that incorporates alternative hypotheses and/or existing hypotheses, to make a qualitative analysis of how the regional and subregional ground-water flow systems function, and to describe the regional saturated zone ground-water flow system.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.1.4.2 - Subregional two-dimensional areal hydrologic modeling. The objective of this activity is to improve estimates of regional ground-water flow by updating an existing two-dimensional, subregional, parameter-estimation model by incorporating additional hydrogeologic data.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.1.4.3 - Subregional two-dimensional cross-sectional hydrologic modeling. The objective of this activity is to estimate the ground-water flow direction and magnitude along a potential flow path through the repository block to the accessible environment, and extending into the region, to help test the assumption of horizontal flow.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.1.4.4 - Regional three-dimensional hydrologic modeling. The objective of this activity is to construct a three-dimensional model of the regional ground-water flow system of Yucca Mountain and vicinity.

The three-dimensional hydrogeologic framework model of the Death Valley regional ground-water flow system, developed in support of numerical modeling efforts, continued to be updated. Interpretive data for the framework model, including maps of the regional potentiometric surface and vegetation, were documented and submitted for review. A report on regional recharge and discharge areas was prepared (D'Agnese et al., 1996a). Another report (D'Agnese et al., 1996b) describes model calibration. Reports releasing digital elevation data (Turner et al., 1996a) and digital hydrographic, land-use, and hydrologic-boundary data (Turner et al., 1996b) were prepared and published. The effects of faulting on the regional flow system were investigated (Faunt, in press).

Calibration of the numerical flow model continued using the MODFLOWP code for parameter estimation. Several additional conceptual models of the regional flow system were tested. Regional structural features (Faunt, in press) were added to the model and were found necessary to accurately simulate the flow system. Structural features were represented in the model as high or low hydraulic-conductivity zones. External boundary conditions were investigated, and the northern boundary of Emigrant Valley was determined to be a no-flow boundary. Previously, the nature of this boundary was in question. A constant-head boundary was required at Pahranaagat Valley, and as a result, substantial flow crossed the model boundary. Various conceptual models and parameters were investigated, and available data support cross-

boundary flow. The nature of a possible internal boundary beneath the southern Funeral Mountains was investigated. The model would not support this feature being a no-flow boundary and indicated that flow occurs through this area into Death Valley, particularly in the deepest layer of the model. The flow model was sensitive to estimated recharge and, because of this sensitivity, the model provided substantial information about recharge. On the basis of model behavior, MODFLOWP was initially queried to estimate 17 parameters, but the number was reduced when it became apparent that the model was insensitive to some of the parameters. The calibrated model provided estimates of nine parameters, including six for hydraulic conductivity, one for anisotropy, and two for recharge. Observed water levels were generally matched within 50 m in areas of small-to-moderate hydraulic gradients. Individual data points were not as accurately simulated in areas with larger hydraulic gradients, but all observed gradients were simulated within 60 percent. Simulated springflow was about 50 percent of estimated springflow, but springflow may have been somewhat overestimated.

A comprehensive report (D'Agnese et al., in press) on model construction and calibration was prepared, reviewed, and submitted for publication approval.

Forecast: Work on this activity will continue during FY 1997. Intended activities include (a) determining the effects of future climate changes on the regional flow and on boundary conditions for the site-scale flow model, and (b) determining the effects of future pumping on regional flow and on boundary conditions for the site-scale flow model. Pending availability of funding, the reports in press will be published and the comprehensive report (D'Agnese et al., in press) completed.

3.1.5 Study 8.3.1.2.2.1 - Characterization of Unsaturated-Zone Infiltration

The objectives of this study are to determine the effective hydraulic conductivity, storage properties, and transport properties as functions of moisture content or potential, and to determine the present and estimate the future spatial distribution of infiltration rates over the repository block.

The primary goal of the reconfigured study is to define the upper-boundary conditions for the site unsaturated zone hydrologic system, in terms of spatial and temporal distribution of moisture flux, for use in site-scale models of unsaturated zone ground-water flow and transport. The integration of hydrologic-process models for the surface and near-surface environments with mapped surficial-material hydrologic properties and mapped present-day net infiltration rates (in terms of both matrix and fracture flow) will provide the basis for a stochastic-deterministic simulation of future upper-boundary conditions, including the probability and magnitude of potential fast pathways of net infiltration. Once the infiltration flux at the upper boundary of the unsaturated zone has been defined, the site-scale model could be used to simulate flow across the potential repository horizon for the set of conditions chosen.

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Activity 8.3.1.2.2.1.1 - Characterization of hydrologic properties of surficial materials.

The objective of this activity is to characterize the infiltration-related hydrologic properties and conditions of the surficial soils and rocks covering Yucca Mountain.

A preliminary surficial-materials properties map of the Yucca Mountain area (Guertal and Davies, 1996) was submitted to the Technical Data Base. The map shows the spatial distribution of eight statistically determined soil units based on the U.S. Department of Agriculture's Soil Taxonomy system. The data used in the properties map consist of field and laboratory measurements of selected properties of the surficial material, including grain-size distribution, rock-fragment content, calcium-carbonate content, water-holding capacity, geomorphic position, slope, and depth to bedrock. For each of the physical and hydrologic properties, a table was prepared listing average values, standard deviations, coefficients of variation, and ranges of values. The map was produced with the ARC/INFO Geographic Information System using the field and laboratory data in conjunction with available surficial-geology maps. The map and the accompanying statistical data are important input to the numerical infiltration model (Activity 8.3.1.2.2.1.2).

Activity 8.3.1.2.2.1.2 - Evaluation of natural infiltration. The objective of this activity is to characterize present-day infiltration processes and net-infiltration rates in the surficial soils and rocks covering Yucca Mountain.

Net infiltration is the amount of natural surface-infiltrated water less losses to evapotranspirative and other processes such as circulation of air within the porous rock mass. Study results indicate that the properties and processes most important for determining net infiltration are the timing and amount of precipitation, the storage capacity of the soil (which includes soil depth), the seasonality and amount of evapotranspiration, and the hydrologic properties of the underlying bedrock.

Infiltration Distribution

A report (Hudson and Flint, in prep.) describes the estimation of shallow infiltration from analysis of monthly neutron-moisture-meter logs collected at 69 borehole locations around Yucca Mountain between October 1984 and April 1995. Shallow infiltration is defined as natural, surface-infiltrated water that has percolated to a depth of at least 2 m into the bedrock closest to the surface. Periodic point estimates of shallow infiltration were obtained between consecutive neutron-moisture logs by subtracting the borehole water (mm) for any measurement from the borehole water for the preceding neutron-moisture log. For each neutron log, borehole water (mm) was calculated as the summation of point measurements of water content (m^3/m^3) multiplied by the distance between measurements (mm) from 2.0 m below the unconsolidated surficial materials-bedrock contact to the bottom measurement. An annual estimate of shallow infiltration was calculated for each borehole as the summation of all periodic estimates for a water year (October 1 of the preceding year to September 30). A multiple linear regression model was developed to correlate annual shallow-infiltration estimates with annual precipitation, depth to bedrock, geomorphic position, the bedrock geohydrologic unit underlying the unconsolidated surficial materials, borehole elevation, and borehole aspect. Maps were

developed for a 230 km² study area around Yucca Mountain to describe the distribution of average annual precipitation with a 161 mm average annual precipitation over the entire study area.

Using this approach, the average shallow infiltration over the entire study area was calculated to be 11.6 mm/yr with the distribution as shown in Table 3-3. Although not apparent from Table 3-3, 93 percent of the total estimated infiltration occurs in areas with less than 0.5 m of unconsolidated surficial materials; these areas account for 48 percent of the study area. Less than 1 percent of the total estimated shallow infiltration occurs in areas with greater than 3.0 m of unconsolidated material; these areas account for 54 percent of the study area. Channels account for only 1 percent of the total shallow infiltration.

Table 3-3. Distribution of Shallow Infiltration

Percentage of Study Area	Amount of Shallow Infiltration (mm/yr)	Percentage of Total Shallow Infiltration
43.7	0	0
5.6	0 - < 10	3.5
26.1	10 - < 20	37.0
13.4	20 - < 30	28.2
11.2	30 - 45	31.3

Potential fast pathways for shallow infiltration were identified as the mapped faults in a smaller 103 km² area within the study area. Thirty-meter-wide fault zones occupy 9.5 percent of this smaller area. These fault zones were combined with the intersecting area of the shallow infiltration map to locate potentially active fast pathways for shallow infiltration identified as fault zones in areas of high shallow infiltration. Of the total area in fault zones, 31.9 percent is in areas with shallow infiltration of >20 to 45 mm/yr, 40.0 percent is in areas with shallow infiltration from >10 to 20 mm/yr, and 28.1 percent is in areas with shallow infiltration from 0.0 to 10.0 mm/yr.

Infiltration Processes

A report (Flint et al., in prep.) was submitted to DOE/Yucca Mountain Site Characterization Office (YMSCO) for review and acceptance. The report describes the effects on predicted rates of net infiltration of several of the observed processes, including precipitation, runoff, evapotranspiration, and redistribution of water within the shallow unsaturated zone. The conceptual model was developed to explain available infiltration data and was tested using a numerical model based on energy- and water-balance calculations. Results indicate a satisfactory preliminary calibration of both a detailed and a simplified numerical model of infiltration for the

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more than 250,000 thirty-m grid cells in the $>230 \text{ km}^2$ study area. Stochastic simulations of precipitation have provided insight into the temporal and spatial distribution of net infiltration throughout the area of Yucca Mountain under both current-climatic and wetter conditions. Simulation results indicate that for an average precipitation year (approximately 160 mm), net infiltration ranges from zero, where alluvial thickness is 6 m or more, to more than 80 mm/yr where thin alluvium overlies highly permeable bedrock on north-facing slopes at high elevations. For the same set of simulations, net infiltration averages 4.5 mm/yr over the Yucca Mountain study area. On a year-to-year basis, average net infiltration varies from zero in dry years to more than 20 mm/yr during years when precipitation exceeds 300 mm. The neutron-borehole locations at Yucca Mountain were modeled using the precipitation for the current climate model (approximately 160 mm/yr) and produced an average net infiltration of 5.5 mm/yr. The simulated future climate (approximately 330 mm/yr) produced an average net infiltration of almost 30 mm/yr, indicating that a doubling of annual precipitation would increase the rate of net infiltration by a factor of five to seven.

Activity 8.3.1.2.2.1.3 - Evaluation of artificial infiltration. The objective of this activity is to characterize water movement in the surficial materials of Yucca Mountain under controlled conditions. Experiments designed to determine the total water flux, flow velocities, and flow paths will be performed on the geohydrologic-surficial units under both present-day precipitation rates and simulated higher rates corresponding to wetter climatic conditions.

With reconfiguration of the study, this activity is now limited to field validation of the infiltration model described in Activity 8.3.1.2.2.1.2 for simulated wetter conditions. Therefore, this activity will be treated as an out-year activity until field-validation studies begin.

Forecast: The report describing the numerical infiltration model will be processed for publication as a USGS Water-Resources Investigations Report. The numerical infiltration model will be refined as appropriate to support the site-scale, unsaturated zone flow model. Transfer functions relating precipitation and other climatological variables to infiltration will be developed for the application of the numerical infiltration model to the site-scale, unsaturated zone flow model.

3.1.6 Study 8.3.1.2.2.2 - Water Movement Test

The objective of this study is to obtain information from isotopic measurements of soil, tuff, and water samples collected to help quantify the amount of percolation into the unsaturated zone at Yucca Mountain.

Activity 8.3.1.2.2.2.1 - Chloride and chlorine-36 measurements of percolation at Yucca Mountain. The objective of this activity is to help quantify the amount of percolation into the unsaturated zone at Yucca Mountain. The data will be used as part of the input to characterize the movement of water through the unsaturated zone at Yucca Mountain.

Analyses of Exploratory Studies Facility Samples

Data collection to support FY 1996 deliverables was completed up to Station 45 + 70 (4570 m), and a paper summarizes the chlorine-36 studies in the ESF (Fabryka-Martin et al., in prep.[a]). The chlorine-36 data were used to assess ground-water travel times and identify potential fast paths for infiltrating water. "Systematic" rock samples were collected every 200 m throughout the tunnel, and "feature-based" samples were collected from specific geologic features such as faults, fractures, and lithophysal cavities. Project hydrologists found that all the systematic samples, as well as most of the feature-based samples, contained chlorine-36 levels consistent with travel times exceeding a few thousand years. Upper age limits ranged up to several hundred thousand years. Uncertainties about temporal variations in the atmospheric chlorine-36 to chloride input ratio prevented calculating more refined estimates of ground-water travel times. Chlorine-36 from weapons testing occurs in a few distinct fractured and/or faulted zones, indicating that at least a small proportion of the water that carried chlorine-36 from weapons testing to these locations is less than 50 years old. Locations at which multiple samples show indications of chlorine-36 from weapons testing appear to be associated with the Bow Ridge fault, the Drill Hole Wash fault, and the Sundance fault. Technetium-99 from weapons testing was detected in the Bow Ridge fault where the fault is exposed in the ESF. The presence of technetium at this location corroborates the presence of chlorine-36 from weapons testing.

The report (Fabryka-Martin et al., in prep.[a]) also discusses the results of flow-and-transport modeling using the FEHM computer code to simulate transport of chlorine-36 into the ESF. Modeling results indicate that observed chlorine-36 signals are consistent with existing site conceptual models and parameter estimates. Infiltration rates between 1 and 5 mm/yr are more consistent with the chlorine-36 to chloride ratios measured in the ESF samples than with infiltration rates on the order of 0.1 mm/yr. Simulations, using base-case parameters, predicted Pleistocene-aged water in the ESF, while parameter changes consistent with increased fracturing of the PTn unit (as might be associated with faults) predicted a small component of chlorine-36 from weapons testing in ESF fractures. Thus, these modeling results show that the new chlorine-36 data presented in this report do not require a major re-evaluation of previous work. The report presents a conceptual model of hydrologic flow that is consistent with the observed chlorine-36 distribution, as well as with transport calculations using a reasonable set of hydrologic parameters and boundary conditions.

A paper was prepared that describes sampling, analysis, and interpretation of more than 500 chlorine-36 to chloride ratio measurements, conducted under this activity from 1990 to the present (Fabryka-Martin et al., in prep.[b]). The paper describes analyses of surface soils and soil profiles; rock samples collected on the surface, from boreholes, and within the ESF; water samples including rainfall, soil moisture, unsaturated zone pore water, and perched water; and pack-rat midden amberat. These results, in conjunction with those from other Project studies, help define a conceptual model of flow and transport in the unsaturated zone.

The report (Fabryka-Martin et al., in prep.[b]) also discusses how measurements of chlorine-36 from weapons testing provide evidence for fast pathways in the various volcanic units. For example, fast transport through the TCw is indicated by chlorine-36 to chloride ratios

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indicating the presence of chlorine-36 from weapons testing in the PTn, which lies below the TCw. This evidence is supported by low pore-water chloride concentrations in samples collected from the PTn. The correlation of these measurements with the surface expression of faulting indicates that the pathway and travel time may involve locally modified PTn fracture properties. These data support the hypothesis that faulting or other disturbances increase PTn fracture permeability, thereby generating a local environment in the PTn that supports fracture flow and potentially more rapid transport of solutes. Fracture permeability in the PTn may provide a concentrating mechanism for liquid water that would favor fracture flow in the underlying TSw, thereby providing continued pathways to the ESF.

While the existence of chlorine-36 from weapons testing enables the study of solute transport with travel times of 50 years or less, the natural cosmogenic background chlorine-36 permits analysis of much longer-term transport processes (Fabryka-Martin et al., in prep.[b]). However, the use of chlorine-36 to chloride ratios for dating older waters is not as straightforward as is testing for weapons testing signals because of variations in the time dependence of the input signal. The present-day meteoric chlorine-36 to chloride ratio at Yucca Mountain is approximately 500×10^{-15} . Theoretical considerations, as well as measurements of soil profiles and materials from ancient pack rat middens, support the assumption that this ratio has remained relatively constant during the Holocene (last 10 ka). Expected lower rates of stable chloride deposition during the Pleistocene (10 ka to 2 Ma) led to higher meteoric chlorine-36 to chloride ratios than were present throughout the Holocene. Superimposed on this effect was the varying production of atmospheric chlorine-36 caused by variations in the geomagnetic field of earth. Using these two factors, the meteoric chlorine-36 to chloride ratio at Yucca Mountain has been reconstructed for the last 1.8 Ma. Chlorine-36 to chloride analyses of packrat midden samples dated by the carbon-14 technique are generally consistent with the reconstruction, although these data can only cover the last 50 ka because of the comparatively short half-life of carbon-14.

The estimates of the age of perched water corroborate estimates of other pore water ages for which chlorine-36 to chloride ratios have been sampled (Fabryka-Martin et al., in prep.[b]). In leachates from crushed rock samples from the ESF, excluding the few samples with unequivocal weapons testing chlorine-36 signals, most samples had chlorine-36 to chloride ratios greater than present-day levels in infiltrating water. A lower bound on the age is about 10 ka because that is the estimate of when the signal in infiltrating water would have been high enough to provide the chlorine-36 to chloride ratio signature found in that water. An upper bound on the age would be several hundred thousand years, which is the time it would take for radioactive decay to decrease the chlorine-36 to chloride ratio from the estimated highest possible ratio to the current ratio. However, carbon-14 measurements of pore water, and independent estimates of infiltration rate in conjunction with transport simulations, indicate that the lower bound is a more probable estimate.

Forecast: Project scientists will continue collecting and analyzing samples from the ESF to test or confirm hydrologic-flow hypotheses based upon previous results. Borehole samples will be collected and analyzed, as appropriate. The contribution of the chlorine-36 produced in situ (e.g., from soil calcite) to the subsurface concentrations of this isotope will be evaluated.

Existing chloride and chlorine-36 data for boreholes and the ESF will be interpreted in terms of infiltration rates to identify potential fast-transport paths from the surface to the sampled depths. Chlorine-36 distributions will be correlated with lithology, structural features, and past climate. Corrected ground-water travel time estimates will be produced using data from chlorine-36 samples from boreholes and the ESF. Synthesis of chlorine-36 sample analyses will be completed. Hydrologic analysis and simulation activities will be performed using FEHM to enhance the interpretation of chlorine-36 results. Hydrologic and solute transport modelers will be included to ensure appropriate use of isotopic results in model validation exercises and in the various hydrology synthesis reports, and to ensure consistency in interpretation of results from this activity with geochemical and isotopic results obtained by other activities.

Elevated chlorine-36 occurrences, possibly from weapons testing, will be corroborated using other environmental tracers such as iodine-129 and technetium-99. Input functions for these tracers will be developed, as appropriate, to compare their timing and magnitude to that for chlorine-36 attributed to weapons testing.

The results of this study will be applied to the validation of site-scale hydrologic flow and solute transport models being developed under other activities.

3.1.7 Study 8.3.1.2.2.3 - Characterization of Percolation in the Unsaturated Zone—Surface-Based Study

The objectives of this study are to determine the present in situ hydrologic properties of the unsaturated zone hydrogeologic units and structural features; to determine the present vertical and lateral variation of percolation flux through the hydrogeologic units and structural features; to investigate the relation between present flux and past climatic conditions; and to determine the effective hydraulic conductivity, storage properties, and transport properties as functions of moisture content or potential.

Activity 8.3.1.2.2.3.1 - Matrix hydrologic properties testing. The objectives of this activity are to conduct laboratory measurements of rock-matrix hydrologic properties on borehole and ESF samples from all hydrogeologic units in the unsaturated zone to characterize the spatial distribution of hydrologic properties within the unsaturated zone.

This activity has been focused to provide two primary information products: (a) a data base of rock matrix hydrologic properties from a series of boreholes that is qualified for site characterization use, and (b) an interpretation of the hydrologic properties of specific hydrogeologic units. Hydrogeologic units have been determined on the basis of similarities within and differences between lithostratigraphic units for the purpose of developing hydrologic flow models.

During the reporting period, a report (Flint, in prep.) was submitted to DOE/YMSCO for review and acceptance. The report describes how 30 discrete layers with similar hydrologic properties were defined within the unsaturated zone at Yucca Mountain on the basis of core-

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scale, matrix hydrologic properties. The 30 hydrogeologic units are easily located in space using three-dimensional lithostratigraphic models based on relationships between the properties and the lithostratigraphy. These units, with some exceptions in the Prow Pass Tuff and Bullfrog Tuff, are intended to be hydrologically distinct enough to be used to design large- and small-scale numerical models to simulate liquid flow at Yucca Mountain. Bulk density, porosity, particle density, saturated hydraulic conductivity, moisture-retention characteristics, saturation, and water potential were determined for each unit from rock cores. The hydrogeologic units were defined using the (a) properties data base developed from 4892 rock samples collected from the coring of 23 shallow and 8 deep boreholes, (b) description of the lithostratigraphic boundaries and corresponding porosity relationships, (c) recognized transition zones for properties that change rapidly with depth, (d) characterized influence of mineral alteration on hydrologic properties such as permeability and moisture-retention characteristics, and (e) statistical analysis that minimized the variance of any property within the layers.

Mean values and standard deviations of bulk density, porosity, particle density, saturation, water potential and saturated hydraulic conductivity were calculated for each hydrogeologic unit, as well as representative values of van Genuchten moisture-retention-curve-fit parameters. Porosity was the most useful property in characterizing individual hydrogeologic units because of its well-defined relationship to the lithostratigraphy and depositional and cooling history of the volcanic deposits. To develop functions that could be used to adequately characterize zones where properties change over short distances, the relationships of porosity to conductivity and the van Genuchten parameters were analyzed. As a result, hydrologic properties specific to the volcanic rocks at Yucca Mountain have been characterized to provide modeling parameters representing all significant hydrogeologic units and important variations within them.

Several other characteristics of the volcanic rocks proved important in defining the hydrogeologic units, shown in Table 3-2. Zones of mineral alteration, especially at the base of the TCw and the zeolitized rocks below the TSw significantly influence the storage and transmission properties of the rock. Transition zones where properties change rapidly but smoothly with depth and zones where properties change abruptly are of particular hydrologic importance because of their tendency to produce capillary or permeability barriers. Such considerations are especially important at the top and bottom of the PTn hydrogeologic unit, where lateral diversion of downward percolation is possible. In addition, zones of vapor-phase alteration were characterized on the basis of changes in porosity.

The parameters of the hydrogeologic units developed in this study and the relationships between flow properties and porosity described can be used to produce detailed and accurate representations of the core-scale hydrologic processes ongoing at Yucca Mountain.

Activity 8.3.1.2.2.3.2 - Site vertical borehole studies. The objectives of this activity are to define the distribution of pneumatic pressure, temperature, and water potential within the site unsaturated zone; and to determine in situ bulk-permeability and bulk-hydraulic properties of the combined fracture and matrix of the media within the site unsaturated zone.

Drilling

There was no site unsaturated zone drilling activity during the reporting period; this was an unfunded activity.

Vertical Seismic Profiling

A report (Balch et al., 1996) was completed that described processing of vertical seismic profiling data from borehole UE-25 UZ#16. The seismic profiling produced several preliminary and partial images of the subsurface west of UE-25 UZ#16. Shear-wave velocities were determined from near-offset records to support interpretation of the high-resolution seismic reflection profiling in the central block of Yucca Mountain (see Activity 8.3.1.4.2.2.1; Section 3.3.4 of this progress report). Analytical work on the seismic reflection data emphasizes correlating of reflections from different levels in the borehole and of reflecting events at various offsets from the borehole. However, final stratigraphic correlations for these partial seismic images have yet to be determined.

Borehole Instrumentation and Monitoring

Pneumatic-interference effects induced by the tunnel boring machine have been observed in both USW SD-12 and USW UZ-7a, located near the main drift about 500-1000 m south of its midpoint. At USW SD-12, the interference effects were first observed during the last reporting period (on or about February 26, 1996) when the tunnel boring machine was approximately 330 m northeast of this borehole (DOE, 1996b; Progress Report #14 p. 28). Unlike interference effects from the tunnel boring machine that have been observed elsewhere, the disturbances in the pneumatic-pressure record at USW SD-12 were initially very subtle and slowly increased over a period of approximately one month. On March 23, 1996, these disturbances reached a maximum and overwhelmed the ambient pressure signal. On this date, the tunnel boring machine was approximately 50 m northeast of USW SD-12. The first indication of an interference effect at USW SD-12 coincided with the penetration of an intensely fractured zone (category 4 ground support conditions) within the middle nonlithophysal unit of the TSw [informally designated as the Broken Limb fracture zone (NWTRB, 1996)]. The manner in which the pneumatic disturbance at USW SD-12 developed indicates that this fracture zone is areally extensive. The slow development of the disturbance indicates significant storage capacity (fracture porosity) associated with this fracture system. Fracture permeability is high, but the high bulk-porosity effectively reduces the pneumatic diffusivity of the rock unit, thus attenuating the magnitude of the pneumatic disturbance.

At USW UZ-7a, located in the Ghost Dance Fault Zone, interference effects from the tunnel boring machine were first observed on May 15, 1996, when the tunnel boring machine was approximately 460 m southwest of USW UZ-7a. The detection of the interference event at USW UZ-7a does not coincide with the intersection of any structural feature mapped on the ground surface. The disturbance event, however, does coincide with penetration of category 4 ground support conditions in the main drift between Stations 53 + 04 (5304 m) and 53 + 12 (5312 m).

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Both the temperature and water-potential profiles developed within the TCw at USW UZ-7a and USW SD-12 are quite different from those encountered in the Drill Hole Wash and Pagany Wash boreholes (USW NRG-6, USW NRG-7a, UE-25 UZ#4, and UE-25 UZ#5). Water-potential profiles for USW UZ-7a and USW SD-12 indicate much drier conditions in the TCw than in the underlying PTn and TSw. Below the PTn, water potentials are greater than -5 bars and are nearly constant and independent of depth. Above the PTn water potentials systematically decrease across the TCw toward the ground surface, approaching -20 bars at a depth of 14 m in USW UZ-7a and at a depth of 24 m in USW SD-12, which are the shallowest instrument stations with water-potential data. The water-potential data probably indicate the presence of active air circulation within the upper 60 to 70 m of the ground surface, which is the interval just above the PTn. Time-series temperature data for these two boreholes indicate seasonal trends in borehole temperatures down to depths of 60 to 90 m. These depths are much greater than the depth of conductive penetration of surface seasonal-temperature changes (15 m). Below 15 m, temperature gradients across the TCw are nearly isothermal, indicating active convective heat-flow processes. Therefore, these gradients are probably a reflection of the effects of air circulation.

On May 9, 1996, unusual oscillations in water potential and temperature began appearing in the monitoring record of instrument station "D" located in the PTn at a depth of approximately 140 ft (43 m) below ground level in USW NRG-7a. The oscillations were characterized by large excursions in water potential, -2 bars to less than -75 bars, with concurrent excursions in temperature. The largest temperature drop observed was 0.7°C. These oscillations tracked barometric pressure changes and persisted for approximately one month. Since early July, water potentials and temperatures have been slowly recovering to their pre-disturbed states. There appears to be no correlation between the anomalous behavior of this instrument station and construction activities in the ESF. Instrument malfunction has been completely eliminated as a possible explanation. The data indicate that the disturbance must have originated from above the instrument station and is being attributed to enhanced communication of this instrument station with the outside atmosphere caused by the drainage of fractures in the overlying TCw. The significance of these observations relates to the expected behavior of flow and transport pathways under varying conditions of saturation, as would be expected to occur with changes in climate or under a transient thermal load. Gas and liquid movement are, to an extent, mutually exclusive because the liquid phase blocks the gas phase and vice versa. Interactions between phases are, therefore, of interest.

Hydrologic Data Acquisition System

Raw-data packages for all monitored boreholes were prepared for the periods October 1, 1995, through March 31, 1996, and April 1, 1996, through August 15, 1996. A special data package, consisting of 455 data files, was also prepared, which incorporates all the pneumatic pressure, thermistor temperature, dry-bulb temperature and water-potential data collected as of July 15, 1996. This data is to be incorporated into the site-scale, unsaturated-zone flow model of Yucca Mountain. A basic-data report was prepared for transmittal to the Project Records Processing Center and Technical Data Base. This report contains reduced data from (a) USW NRG-7a and USW NRG-6 from September 12, 1995, through March 10, 1996; (b) UE-25 UZ#4

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and UE-25 UZ#5 from June 20, 1995 through March 10, 1996; (c) USW UZ-7a from October 20, 1995, through April 30, 1996; and (d) USW SD-12 from November 20, 1995, through April 30, 1996. Monitoring at USW NRG-6 was discontinued during the first week of September 1996. Gas sampling was conducted at USW SD-12 in May and July 1996, emphasizing the deepest parts of the TSw and the CHn.

Surface-Based Air-Permeability Testing

The surface-based gas-injection testing program has been discontinued. The final report (LeCain, in press) describes air injection testing in vertical boreholes in welded and nonwelded tuff. Air-injection permeability values for most of the hydrologic units at Yucca Mountain are provided in Table 3-4. Results indicate some structural control with depth on the permeability distribution within the TSw, possibly associated with the depositional and cooling features of the tuff.

Table 3-4. Air Permeability Values for Hydrogeologic Units

Hydrogeologic Unit	Permeability Range (10^{-12}m^2)
Tiva Canyon welded (TCw)	0.3 to 54.0
Paintbrush nonwelded (PTn)	0.12 to 3.0
Topopah Spring welded (TSw)	0.02 to 33
Calico Hills nonwelded (one interval only) (CHn)	0.025

The air-injection permeability values of the welded tuffs of the TCw and TSw are three to six orders of magnitude greater than the laboratory permeability values of the tuff matrix, indicating that fractures are responsible for most of the bulk permeability. The air-injection permeability values of the PTn are generally higher than laboratory matrix permeability values, indicating that there are open fractures in the PTn.

Values of air permeability obtained through analysis of pneumatic-monitoring data from instrumented boreholes are an order of magnitude larger than those obtained through air-injection testing, indicating that the TSw is anisotropic with a vertical-to-horizontal permeability ratio of about 10:1.

Integrated Data Analysis and Interpretation

A report (Rousseau et al., in prep.) describes the results of surface-based geologic, pneumatic, hydrologic, and geochemical studies conducted near the north ramp of the ESF. These results are pertinent to understanding multiphase fluid flow within the unsaturated zone. The most significant results of these studies are summarized in the following paragraphs.

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Multiple lines of evidence indicate that gas and liquid flow within the welded tuffs of the unsaturated zone occur primarily through fractures. Although fracture density is much lower in the PTn than in the overlying and underlying densely welded TCw and TSw, pneumatic and aqueous-phase isotopic evidence indicate that substantial secondary permeability can occur locally in the PTn, especially in the vicinity of faults. In situ pneumatic-pressure monitoring indicates that the unsaturated zone pneumatic system consists of four subsystems that coincide with the four major hydrogeologic units: TCw, PTn, TSw, and CHn (see Table 3-2).

Deep percolation occurs as episodic pulses of inflow that propagate rapidly to depth, apparently bypassing much of the rock matrix. Field-scale and core-scale water potentials throughout much of the PTn and TSw are very high, generally greater than -3 bars, and are nearly independent of depth. The combination of high fracture permeability, high water potentials, high matrix saturations, and low matrix permeabilities results in a percolation environment conducive to sustaining deep fracture flow. The episodic pulses of inflow are evidenced in the sporadic but nevertheless commonplace occurrence of water with concentrations of radioactive isotopes indicative of origins post-dating the onset of atmospheric testing of nuclear weapons. High concentrations of tritium have been detected at many horizons within the PTn and in the top of the TSw. More dilute concentrations, indicating the mixing of water containing tritium from weapons testing with older water, have been detected in the deeper sections of the TSw and in the CHn. (See also Section 3.1.11 (Activity 8.3.1.2.2.7.2) of this progress report.)

Evidence for fracture flow also is apparent in the widespread occurrence of perched water with chemical and isotopic signatures that indicate a fracture-flow origin for at least some of this water. In the north ramp area, perched water has been encountered at the base of the TSw or in the top of the underlying nonwelded to partially welded tuffs of the CHn in every dry-drilled borehole that penetrates the TSw-CHn contact. Both the chemical and isotopic compositions of perched water indicate that this water was derived primarily from fracture flow with little or no contribution from water in the matrix of the overlying rock. Carbon-14 ages of perched water range from 3000 to 7000 years. Strontium-87 to strontium-86 isotope ratios indicate dissolution of surficial pedogenic calcite and calcite fracture fillings, supporting a fracture-flow origin for perched water. Moreover, carbon-13 and deuterium values indicate rapid infiltration into fractures with little or no prior evaporation.

Evidence for deep fracture flow into the CHn at USW UZ-14 is indicated by the occurrences of carbon-14 values that are between 80 and 95 percent modern carbon, equivalent to apparent ages of about 1800 and 400 years. These ages are younger than age estimates for perched water in the overlying TSw and are much younger than ages that could be derived from a matrix-flow model.

Two features of the original conceptual model for unsaturated flow at Yucca Mountain are lateral flow within the PTn, and interception and diversion of flow downward along structural pathways. Evidence is lacking for extensive lateral flow within the PTn and for interception and diversion of this flow downward along structural pathways (faults). Where data are available to infer lateral flow in the PTn, it is not clear whether or not fracture flow may have produced the observed results. Pneumatic data, derived primarily from the analysis of the interference effects

from construction of the north ramp, indicate that faults within the TSw are open over substantial distances and are very permeable. Tunnel-induced pneumatic disturbances have been propagated along these faults over distances that exceed 500 m. These disturbances also have been detected in the pneumatic-pressure record of the overlying PTn in the vicinity of these faults. In spite of this, the existing data have not confirmed or refuted the hypothetical role of these structures in intercepting lateral flow from within or from above the PTn and diverting this flow downward.

On the basis of measured temperature gradients within the TSw, deep percolation appears higher beneath active channels of major drainages, and diminishes toward the channel margins and hillslopes bordering these channels (see Activity 8.3.1.2.2.1.2, Section 3.1.5 of this progress report). Numerical simulations indicate that this downward percolation appears to be accompanied by lateral spreading as the percolation front moves downward through the PTn and across the contact between the PTn and underlying TSw. Temperature data from the well-documented field site in Pagany Wash indicate the presence of a significant heat-flow deficit between the PTn and underlying TSw that is probably caused by nonconductive heat-flow processes which have substantial capacity to extract heat. Percolation fluxes are on the order of 10 to 20 mm/yr beneath the Pagany Wash channel and on the order of 5 mm/yr or less beneath the hillslopes bordering this drainage. These deficiencies may account for the apparent heat-flow deficit. Analyses of borehole temperature gradients in Drill Hole Wash indicate similar percolation fluxes and flux distributions within that drainage. However, an analysis showed that the perched-water reservoir under Drill Hole Wash could be sustained by percolation fluxes through the Topopah Spring Tuff of as little as 0.001 to 0.29 mm/yr, using residence times estimated from uncorrected carbon-14 activities of perched-water samples and volume estimates for the structurally controlled reservoir.

Activity 8.3.1.2.2.3.3 - Solitario Canyon horizontal borehole study. The objectives of this activity are to determine the extent of fracturing, brecciation, and gouge development in the Solitario Canyon fault zone; to evaluate the effects of fault zone on ground-water movement in the unsaturated zone; and to identify additional fault-zone-related data needs.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Measurements of matrix-hydrologic properties will be performed on core samples from test holes drilled in ESF alcoves, particularly from the alcoves excavated into the Ghost Dance fault from the main drift. Matrix-properties data will be used to help place boreholes and instrumentation for the ESF radial boreholes and major faults tests. The data also will be used to aid interpretation of the results of hydrochemical and air-permeability testing. Limited flow-properties determinations will be performed on existing rock-core samples. Emphasis will be on measuring unsaturated hydraulic conductivities using the ultra-centrifuge and on determining water-retention relationships for samples from the vitric and zeolitic facies of the CHn. These core samples will come from boreholes USW SD-9, USW SD-12, and USW SD-7.

Pneumatic-pressure, temperature, and water-potential monitoring will continue into FY 1997 at USW NRG-7a, UE-25 UZ#4, UE-25 UZ#5, USW UZ-7a, and USW SD-12. Data

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packages containing raw sensor readings and reduced values of monitoring data will be submitted to the Project Records Processing Center and Technical Data Base, as appropriate. Monitoring of UE-25 UZ#4, UE-25 UZ#5, and USW NRG-7a may be discontinued before the end of the next semi-annual reporting period. Monitoring of the Hydrologic Research Facility prototype boreholes in Area 25 will be discontinued during the first week of October 1996, completing the planned five-year evaluation period for this prototype test. Borehole monitoring data will be reduced and analyzed, including evaluations of barometric-pressure damping and lagging with depth, temperature gradients and stability, and water-potential equilibration behavior with respect to the stratigraphic units and depths at which instrument stations are located. The major effort during the next six months will be writing a report that describes the hydrology of the unsaturated zone in the main drift area of the ESF.

3.1.8 Study 8.3.1.2.2.4 - Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility

The objectives of this study are to supplement and complement the surface-based hydrologic information needed to characterize the Yucca Mountain site, and to provide information for analyzing fluid flow and the potential for radionuclide transport through unsaturated tuff.

A report describing the hydrogeology of the unsaturated zone of the north ramp area was completed (Rousseau et al., in prep.).

Activity 8.3.1.2.2.4.1 - Intact-fracture test in the Exploratory Studies Facility. The objective of this activity is to evaluate fluid-flow and chemical transport properties of single, relatively undisturbed fractures.

The purpose of the work is to characterize fluid flow along both undisturbed fractures and those under stress, and to provide these properties to help calibrate models for fluid flow in fractured rock at various scales.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.2.4.2 - Percolation tests in the Exploratory Studies Facility. The objective of this activity is to determine the hydrologic conditions that control the occurrence of fluid flow in fractured tuff units, and to provide experimental data against which the validity of conceptual and numerical models may be tested.

To evaluate the moisture conditions in the tunnel and to provide boundary conditions for drift-scale and site-scale models, relative humidity, temperature, pressure, and air velocity data are being collected from sensor stations and from scoping surveys along the ESF. The variations in vapor density between different locations, together with a simple approximation for air flow in the tunnel, were used to estimate the moisture removal rate and the equivalent evaporation rate. The weekly amounts of water removed by the ventilation were a substantial fraction of water

used in the tunnel. The estimated equivalent evaporation rates are on the order of 200 mm/yr, with standard deviation greater than 90 mm/yr, for both the TSw unit in a 1400 m section centering around the Thermal Testing Alcove and the PTn in a 380 m section between the Upper Paintbrush (Non-Welded) Contact Alcove and the Lower Paintbrush (Non-Welded) Contact Alcove. The uncertainties in the estimates are related to fluctuations in the moisture introduced by construction activities, including water use and air ventilation.

Activity 8.3.1.2.2.4.3 - Bulk-permeability test in the Exploratory Studies Facility. The objectives of this activity are (a) to determine the scale at which the host rock behaves as an equivalent anisotropic porous medium, (b) to compare hydraulic test results against a distribution of simulated results calculated from a large number of realizations of the possible fracture networks conditioned on average fracture orientation and/or fracture density data, (c) to use a numerical fracture-flow model to establish the minimum dimensions at which other rock masses with the same fracture characteristics behave as equivalent porous media, and (d) to examine the dependence of rock-mass dimensions on changing saturation.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.2.4.4 - Radial borehole tests in the Exploratory Studies Facility. The objectives of this activity are to detect vertical movement of water in both the vapor and liquid phases, and to evaluate the potential for lateral movement of water along hydrologic contacts, as well as to evaluate the radial extent of excavation effects on the hydrologic properties of the unsaturated hydrogeologic units.

Shut-in pressure monitoring has been completed in two near-horizontal radial boreholes (RBT-1 and RBT-4) in the Upper Paintbrush (Non-Welded) Contact Alcove (see Figure 3-4). Preliminary analysis of the pressure record shows that the attenuation and lag are uniform throughout both boreholes, indicating that there are no significant lateral differences in pneumatic-pathway characteristics.

Single-hole pneumatic testing was completed in boreholes RBT-1 and RBT-4 in the Upper Paintbrush (Non-Welded) Contact Alcove. The pneumatic-permeability values are as follows: (a) hackly subzone of the Tiva Canyon lower nonlithophysal zone, 0.5 to $12 \times 10^{-12} \text{ m}^2$, (b) columnar subzone of the Tiva Canyon lower nonlithophysal zone, 0.02 to $41 \times 10^{-12} \text{ m}^2$, and (c) vitric zone of the Tiva Canyon Tuff, 0.4 to $62 \times 10^{-12} \text{ m}^2$. The tests indicate that the vitric nonwelded subzone has secondary permeability caused by fractures. Capillary pressures (expressed as the air pressure required to displace water held by capillarity) are generally less than 1 atmosphere, indicating a higher moisture content than was previously estimated. Several test intervals indicate capillary pressure values of less than 0.2 atmosphere. The capillary pressure data support the concept of isolated water-flow paths.

Activity 8.3.1.2.2.4.5 - Excavation effects test in the Exploratory Studies Facility. The objective of this activity is to monitor changes in both the stress state and fractured-rock permeability caused by excavating the ESF. The objective is to use these data, as well as other physical properties data gathered during the activity, to calibrate and validate a coupled

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hydraulic-mechanical, finite-element model. The model will be used to predict stress and ensuing permeability changes around excavation openings.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.2.4.6 - Calico Hills testing in the Exploratory Studies Facility. The objectives of this activity were intentionally deleted. Testing in the Calico Hills Formation will be described in revisions to other ESF studies.

This activity was deleted from the study plan in Revision 9 of the Site Characterization Program Baseline (DOE, 1995g). (See Appendix H for the Site Characterization Program Baseline history.) Testing in the CHn may be conducted as part of other ESF testing activities.

Activity 8.3.1.2.2.4.7 - Perched-water testing in the Exploratory Studies Facility. The objectives of this activity are to detect the occurrence of any perched-water zones; to estimate the hydraulic properties of the zones; and to determine the implication of the existence of such zones on the flux, flow paths, and travel times.

Monitoring for perched water in the ESF main drift (Figure 3-4) and in the Bow Ridge Fault Alcove and the Upper Paintbrush (Non-Welded) Contact Alcove (see Figure 3-4) continued during this reporting period, but no perched water was detected. Samples of rock were collected from several locations along the main drift and distilled to analyze for tritium content. The locations of these samples correlate with those of samples containing elevated chlorine-36 concentrations. The results of tritium analysis from these samples are all near 0.0 tritium units. These shallow samples, collected near the tunnel walls, may have been contaminated by moisture associated with ESF construction water that was obtained from well UE-25 J#13. Therefore, these results are considered inconclusive because tritium from weapons testing was found in the same horizon in a nearby alcove that was isolated from construction water.

Perched water was detected in boreholes USW UZ-1, USW UZ-14, USW SD-7, USW NRG-7a, and USW SD-9 at depths of 383 to 492 m, at least 100 m above the water table. In boreholes USW UZ-14 and USW SD-9, a televiwer log showed water entering the boreholes through discrete fractures. Boreholes USW UZ-14 and USW SD-7 are located near faults that may be acting as structural traps, allowing water to accumulate. The perched-water zones were generally in fractured rock units with impermeable matrices overlying less-fractured rock units with more permeable matrices. This indicates that the relative fracture frequency and fracture permeability strongly influence the accumulation of perched water.

Pumping tests were performed on perched water bodies that were intersected in USW UZ-14 and USW SD-7. These tests were conducted to determine hydraulic conductivity and sizes of the perched water bodies. At USW SD-7, partial recovery of the water level occurred quickly, but the several feet of residual drawdown remained after the tests were completed. Conversely, at USW UZ-14, recovery was complete but slower than in USW SD-7. The recovery results indicate that the perched water body in USW UZ-14 is more extensive than that in USW SD-7, but that the perched water body in USW SD-7 has greater hydraulic conductivity.

Analyses of the perched waters show that the chemical compositions are similar to regional ground water but that concentrations of individual constituents differ. Comparisons of perched-water pore-water chemistry indicate that the water held in the matrix has little influence on perched water, and that the water that accumulates as perched water bodies probably moves quickly through fractures.

Although the perched water detected was significantly deeper than the proposed repository, hydrogeologic conditions are favorable for the formation of perched-water zones at depths that may be reached by the excavation if it is deepened to include Calico Hills tests, which are, however, not anticipated at the present time. Overall, perched water may be widespread near the base of the TSw in the vicinity of the ESF.

Activity 8.3.1.2.2.4.8 - Hydrochemistry tests in the Exploratory Studies Facility. The objectives of this activity are to understand the gas-transport processes within the unsaturated zone and to provide independent evidence of flow direction, flux, and travel time of gas; to design and implement methods for extracting uncontaminated pore fluid from rock excavated during ramp construction; to determine the flow direction of water in the unsaturated zone by isotope geochemistry techniques; and to determine the extent of water-rock interaction so that geochemical modeling can be performed to deduce the flow path and to understand the geochemical evolution of unsaturated zone water.

Ages from carbon-14 analyses on gas samples collected from the first borehole (HPF-1) in the Bow Ridge Fault Alcove (see Figure 3-4) are fairly uniform and range from 500 to 1000 years old. This finding is consistent with the results of the carbon dioxide and carbon-13/carbon-12 analyses, and may be the result of the high effective porosity to air within the Bow Ridge fault or the pre-Rainier Mesa Tuff bedded tuff. Data from gas analyses indicate the carbon dioxide concentration varies with depth (distance) away from the alcove. Carbon dioxide concentrations increase from 0.054 percent at 12 to 17 ft (3.7 to 5.2 m) to 0.101 percent at 80 to 85.57 ft (24.4 to 26.1 m), with a peak of 0.113 percent at 55 to 57 ft, at or near the Bow Ridge fault in the pre-Rainier Mesa Tuff bedded tuff. Results from the analysis of gas samples collected for carbon-13/carbon-12 analyzed also vary with depth away from the alcove, ranging from -11.85 at 12 to 17 ft (3.7 to 5.2 m) to -12.88 at 80 to 85.57 ft (24.4 to 26.1 m), and a low of -12.91 detected at 55 to 57 ft (16.8 to 17.4 m). Results from the carbon-14 analyses are not yet available.

Gas samples were collected from radial boreholes RBT-1 and RBT-4 in the Upper Paintbrush (Non-Welded) Contact Alcove (see Figure 3-4). In both boreholes, carbon dioxide concentration, carbon-13/carbon-12 ratios, and carbon-14 age do not vary systematically with depth but are widely scattered throughout the boreholes (see Table 3-5). The variability seen is probably related to the fracture frequency encountered in the boreholes, although detailed interpretation of these data has not yet been completed.

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Table 3-5. Summary of Carbon Dioxide and Carbon Isotope Data for Gas Samples from the Upper Paintbrush (Non-Welded) Contact Alcove

Borehole	Depth (ft)	CO ₂ (Avg. %)	¹³ C/ ¹² C (Avg.)	¹⁴ C Age (Years Before Present)
RBT-1	96-99.4	0.096	-13.1	1517
RBT-1	87-89	0.091	-12.6	1016
RBT-1	66-68	0.105	-13.6	1456
RBT-1	47-51.5	0.068	-11.9	1052
RBT-4	92-99.97	0.117	-14.2	2009
RBT-4	57-59	0.107	-13.4	Modern
RBT-4	42-46	0.101	-13.5	1324
RBT-4	22-27	0.122	-14.2	1948

Pore water was extracted from 14 core samples from boreholes RBT-1 and RBT-4 in the Upper Paintbrush (Non-Welded) Contact Alcove. Limited quantities of water were obtained and analyzed for common ions, and tritium and, in one instance, waters from several core samples were combined to analyze for carbon-14. Although not all data are available, concentrations of common ions indicate that the samples contain natural amounts of lithium and bromide, indicating that the samples were not contaminated by ESF-construction water. Tritium concentrations in RBT-1 pore water generally are at or below detection limit (4.0 tritium units). In contrast, tritium concentrations in RBT-4 pore water range up to 11.7 tritium units, indicating some component of post-weapons testing water in these samples. Results of carbon-14 analyses of these samples are not yet available.

Pore water was extracted from four rock samples collected from the moist-rock zone where the north ramp penetrates the PTn unit. Concentrations of common ions are similar to the pore water from the Upper Paintbrush (Non-Welded) Contact Alcove cores. Concentrations of lithium and bromide in these samples indicate that the water is naturally occurring and was not contaminated by ESF-construction water. Tritium concentrations in these samples were all below the detection limit. In contrast, tritium concentrations of pore water obtained from the core of borehole HPF-1 in the Bow Ridge Fault Alcove of the ESF are 118.3 and 128.1 tritium units. The tritium concentration for pore water from a sample of the pre-Ranier Mesa Tuff collected about 10 feet west of the fault is 154.6 tritium units. The tritium concentrations of pore water decline sharply to about 30 tritium units east of the fault and west of the zone in the pre-Ranier Mesa Tuff. Between the fault and the peak in the pre-Ranier Mesa Tuff the tritium concentrations are between 65 and 80 tritium units. These data clearly indicate post-weapons-

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testing infiltration of water into the Bow Ridge fault and generally support the chlorine-36 data for the Bow Ridge fault in the ESF.

Activity 8.3.1.2.2.4.9 - Multipurpose-borehole testing. This activity was originally planned to monitor hydrologic and engineering interference effects from construction of exploratory shafts 1 and 2 on tests in these shafts and interference effects between tests in the shafts. In the current ESF design, with two ramps, testing in a scientific shaft is no longer planned.

This activity was deleted from the study plan in Revision 10 of the Site Characterization Program Baseline (see Appendix H).

Activity 8.3.1.2.2.4.10 - Hydrologic properties of major faults encountered in the main test level of the Exploratory Studies Facility. The objective of this activity is to investigate the permeability and flow conditions of the major faults encountered in ramps and drifts of the ESF.

Shut-in pressure monitoring of the second borehole (HPF-2) in the Bow Ridge Fault Alcove (see Figure 3-4) was completed. Results show little attenuation or lagging of the barometric-pressure signal throughout the borehole, indicating a high permeability for the TCw. These results are consistent with the results of pressure monitoring in surface-based boreholes.

Cross-hole pneumatic testing in the Bow Ridge Fault Alcove (see Figure 3-4) indicates that the permeability of the fault breccia is about $27 \times 10^{-12} \text{ m}^2$ and the porosity is 20 to 29 percent. Tracer tests in the fault breccia show peak arrival travel times of 36 to 80 minutes, indicating that the effective porosity is between 9 to 19 percent. The lower effective-porosity values from the tracer tests indicate some retardation of the tracer gas by the tuff. Cross-hole pneumatic testing in the pre-Rainier Mesa Tuff bedded tuff indicates permeability values of $23 \times 10^{-12} \text{ m}^2$ and a pneumatic porosity of 27 percent. Cross-hole pneumatic testing in the Tiva Canyon middle nonlithophysal and lower lithophysal units indicates permeability values of 22 and $2 \times 10^{-12} \text{ m}^2$, respectively. The cross-hole permeability values agree with the single-hole testing estimates.

A detailed testing strategy for the Northern Ghost Dance Fault Alcove (see Figure 3-4) was developed.

Forecast: Percolation tests will continue in the ESF. Additional sensor stations will be installed in the ESF main drift and along the south ramp. Surveys will be made along the ESF. The moisture data will be analyzed in more detail to monitor the evaporation from the tuff units and from the construction water. Drying processes in the rock will be evaluated.

Air-permeability and hydrochemistry testing will be conducted in alcoves excavated into the Ghost Dance fault from the main drift of the ESF.

3.1.9 Study 8.3.1.2.2.5 - Diffusion Tests in the Exploratory Studies Facility

The objective of this study is to determine in situ the extent to which nonsorbing tracers diffuse into the water-filled pores of the tuffs of the Topopah Spring welded (TSw) unit at the main test level of the ESF. A diffusion test is also proposed in the Calico Hills nonwelded (CHn) unit.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No tests are planned for this activity during FY 1997.

3.1.10 Study 8.3.1.2.2.6 - Characterization of Gaseous-Phase Movement in the Unsaturated Zone

The objectives of this study are to (a) describe the pre-waste-emplacement, gas-flow field in the presence of open boreholes and the ESF excavations; (b) develop an understanding of the factors that produce and affect this flow field, including topographic, stratigraphic, and structural controls; (c) determine transmissive and storative properties for gaseous flow; (d) develop a history of air circulation at the instrumented boreholes from the time of drilling until the holes are stemmed, as an aid in evaluating the time following stemming before ambient conditions are restored, (e) determine fractured, porosity-gas-filled matrix porosity ratios and factors controlling gaseous exchange between the two, and/or the dispersivity of the fracture network to gas flow and transport; (f) determine changes caused in the gas-phase flow field as ESF excavations are advanced beyond open boreholes near the line of the ESF excavations; and (g) to develop a preliminary model of the transport of individual gaseous species.

Activity 8.3.1.2.2.6.1 - Gaseous-phase circulation study. The objectives of this activity focus on the collection and interpretation of several types of data, including composite borehole shut-in pressures, downhole gas-flow velocity surveys, gas-column temperature surveys, packed-off zone shut-in pressures, results from multiple borehole tracer tests, and gas chemistry and isotope chemistry from selected open boreholes and packed-off zones within boreholes. These data will be collected from a number of boreholes on an "as available" basis in order to collect as much data as possible in the boreholes most likely to be affected by ESF construction.

Downhole pressure monitoring continued at boreholes UE-25 NRG#5 and USW SD-7, and gas-chemistry samples were collected from these boreholes. The primary focus of this activity during the reporting period has been data interpretation and preparation of a report that synthesizes the results of pneumatic-pressure monitoring and gas-phase chemical sampling conducted at boreholes UE-25 NRG#5, USW NRG-6, USW NRG-7a, UE-25 UZ#4, UE-25 UZ#5, USW SD-9, USW SD-12, USW UZ-7a, USW SD-7, USW UZ-6, and USW UZ-6s. Near the end of the reporting period, a draft synthesis report (Patterson et al., in prep.) was submitted to DOE/YMSCO for review and acceptance.

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The computed phase lags and residual amplitudes of the in situ pressure response to changes in atmospheric pressure indicate that individual lithostratigraphic units can be grouped into four distinct pneumatic systems: (1) the welded subzones and intervals of the TCw; (2) the PTn, which includes the crystal-poor vitric base of the Tiva Canyon Tuff, the Yucca Mountain and Pah Canyon Tuffs (with associated bedded tuffs), and the crystal-rich top of the Topopah Spring Tuff; (3) the welded lithophysal and nonlithophysal subzones and intervals of the TSw; and (4) CHn, which consists of the pre-Topopah Spring Tuff bedded tuff, the nonwelded tuffs of the Calico Hills Formation, and the pre-Calico Hills Formation bedded tuff.

Pneumatic-pressure records for instrument stations within the TCw display very little attenuation and lag of the synoptic pressure signal, which indicates large bulk permeability and abundant interconnection of fractures. These observations are corroborated by simulation results from the borehole USW UZ-6s model, which indicate that the permeability of different subunits within the TCw range from hundreds to thousands of darcies. Although the highest of these values probably represent fault effects, the values are similar to those determined from one-dimensional analysis of pressure responses measured in boreholes UE-25 NRG#5 and USW SD-7.

Pneumatic-pressure data from instrument stations located within and across various subunits of the PTn indicate that the pressure attenuation and lag in these subunits differ from one location to another. The variation in thickness of the PTn, however, is not sufficient to account for differences in the magnitude of the residual amplitude and phase lag of the synoptic-pressure signal transmitted across this unit. Further, results of one-dimensional model simulations using the AIRK code (Weeks, 1978) indicate that average bulk permeability of the full thickness of the PTn ranges between 0.2 and $1 \times 10^{-12} \text{ m}^2$ at boreholes UE-25 NRG#5, USW NRG-6, USW NRG-7a, USW SD-7, and USW SD-9. These simulation results indicate that the PTn permeability varies within a relatively narrow range over a significant part of the repository area.

Pressure data from instrument stations located in the Topopah Spring lithophysal and nonlithophysal welded tuffs exhibit negligible attenuation and lag once the pneumatic-pressure signals enter those units. Pressure signals appear to be transmitted nearly instantaneously throughout the entire Topopah Spring section, indicating that the fractures within the Topopah Spring Tuff are very permeable and highly interconnected within both the lithophysal and nonlithophysal subunits. These results are consistent with those derived from the north ramp simulation model, which indicates that the bulk horizontal permeability of the Topopah Spring Tuff is 30 to $60 \times 10^{-12} \text{ m}^2$ near boreholes UE-25 NRG#5, USW NRG-6, and USW NRG-7a, with a vertical permeability of 70 to $100 \times 10^{-12} \text{ m}^2$. These results also are consistent with one-dimensional AIRK simulation results, which indicate that the vertical permeability of the Topopah Spring Tuff probably is greater than about $20 \times 10^{-12} \text{ m}^2$.

The pressure record at three stations where pressures are monitored below perched-water zones indicates that essentially all the synoptic-barometric signal is attenuated. This is consistent with the concept that a perched-water zone, because of full saturation, would have extremely low

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permeability to air and would effectively impede the downward propagation of the surface barometric signal.

Despite the relative success of the north ramp model in simulating the magnitude and timing of effects of the north ramp excavation, pressure data for several wells appear to be affected by faults not included in the model. Of the eight boreholes with discretized pressure records discussed in this report, five of them (UE-25 NRG#5, USW NRG-6, USW SD-12, USW UZ-7a, and USW SD-7) are interpreted as having been affected by the presence of the Drill Hole Wash fault or the Ghost Dance fault, both before and after the onset of ESF-excavation effects. The ESF-excavation effects seen in two other boreholes (UE-25 UZ#4 and UE-25 UZ#5) began when the ESF intersected another fault, and connected it pneumatically to those boreholes. These data emphasize that important pneumatic pathways exist in the vicinity of the proposed repository. Thus, even though the north ramp model provides parameter estimates that appear to be suitable for a general simulation model of repository performance, the potential for effects of extremely permeable features provided by faults must be included in such models.

Two numerical models of gas flow in the unsaturated zone have been developed for different geographic areas of Yucca Mountain. The two models are the north ramp model and the Highway Ridge model (Patterson et al., in prep).

Results from the Highway Ridge flow model are similar to those from the north ramp model. The Highway Ridge model closely predicted the peak arrival time for the convergent tracer test between boreholes USW UZ-6 and USW UZ-6s, but it failed to accurately predict flow direction. Also, model results indicated that natural circulation through the TCw comprising Highway Ridge was on the order of four pore volumes annually, or nearly ten times larger than the chemistry-based estimate of about 0.5 pore volumes per year, as determined by Thorstenson et al. (in prep.). As with the north ramp model, results are sufficiently encouraging to indicate that further model development is warranted.

Pressure response data indicate that thermosyphon movement of air occurs from the TSw to the TCw through borehole USW UZ-6. Thermosyphon movement of air occurs in boreholes in hilly terrain that are open through a section of the unsaturated zone. The air movement results from temperature-induced density differences between atmospheric air and rock gas (Patterson et al., in prep.). Note that thermosyphon should not be confused with barometric pumping which occurs in any borehole open to the atmosphere. The air movement indicates that no significant permeability barriers exist in the TSw between its outcrop in Solitario Canyon and the borehole, a distance of 300 to 400 m. These findings indicate that heat generated by waste emplacement in the TSw may produce gas-phase circulation cells between the repository and the outcrop, and these cells would discharge heat, moisture, and carbon-14 dioxide to the atmosphere. The indicated volume of thermosyphon circulation is well calculated using the permeability inferred from pressure responses to the north ramp tunnel, and the result provides further confidence that such permeability values might be useful in a general porous-media-based model to simulate repository performance.

Gas entering the TCw through the opening in the PTn created by the presence of borehole USW UZ-6 can be identified from chlorofluorocarbon chemistry data, as demonstrated by Thorstenson et al. (1995) and confirmed by tracer-test results. These results indicate that additional sampling for chlorofluorocarbons in previously unsampled neutron holes on the crest of Yucca Mountain and in the various lined and stemmed boreholes, may provide important information about gas flow across the PTn. Such data may help determine the air residence time in the TCw and might identify localities where the PTn is breached, allowing increased air circulation between the TSw and the TCw.

Activity 8.3.1.2.2.6.2 - Measurement of near-surface gas flow fields. The objective of this activity was to demonstrate how a water vapor RAMAN-LIDAR can be used to monitor and characterize preferred pneumatic pathways. The ability of this technology to measure the rate of water vapor exchange between the atmosphere and the preferred pathways was validated and was intended to provide benchmark data for convective transport models. This study was to characterize known pneumatic pathways and locate the surficial expression of unknown pneumatic pathways at Devils Hole, Nevada, using RAMAN-LIDAR. This information was intended to aid the hydrology program by locating potential pneumatic pathways at Yucca Mountain.

This activity was developed after the SCP was issued. Draft input to Study Plan 8.2.1.2.2.1 was completed in April 1995, and a scoping study of known gas outflow locations at Devils Hole was completed in September 1995. The results of the scoping study were reported in Progress Report #12 (DOE, 1995h).

This activity was suspended because of reductions in funding. (See Progress Report #13 [DOE, 1996j].)

Forecast: The synthesis report on gas-phase circulation in the unsaturated zone will be completed. Boreholes instrumented with inflatable SEAMIST liners (UE-25 NRG#5 and USW SD-7) [see p. 3-38 of Progress Report #14 (DOE, 1996b)] will be transferred to Activity 8.3.1.2.2.3.2 for continued pneumatic monitoring. No schedule has been developed for removing the liners from these boreholes. No additional work is planned for this study during FY 1997.

3.1.11 Study 8.3.1.2.2.7 - Hydrochemical Characterization of the Unsaturated Zone

The objectives of this study are to (a) characterize the hydrochemistry of the unsaturated zone by determining the transport mechanisms, flow directions, residence times, and travel times for gas and water; (b) determine the extent of water/rock interactions in the unsaturated zone; and (c) develop conceptual hydrologic and geochemical models.

Activity 8.3.1.2.2.7.1 - Gaseous-phase chemical investigations. The objectives of this activity are to understand gas-phase transport mechanisms within the unsaturated zone at Yucca Mountain, as well as to seek evidence of gas-flow direction, volume, rate, and travel time within the unsaturated zone.

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A report (Yang et al., in press) was developed that presents and interprets all gaseous- and aqueous-phase hydrochemical and isotopic data collected from surface-based boreholes through FY 1995.

Gas sampling from instrumented borehole USW SD-12 was completed during two sampling episodes in May and July 1996. USW SD-12 is located near, but slightly south of, the midpoint of the ESF main drift. Carbon dioxide, methane, carbon-13/carbon-12, and carbon-14 gas samples were collected from 16 stations in USW SD-12 from the TCw down through the CHn (see Table 3-2). Carbon dioxide concentrations in the Topopah Spring Tuff are two to three times larger than concentrations observed in USW UZ-1, or about eight times greater than atmospheric concentration. Although the source of carbon dioxide is not known at this time, outgassing of pore water is one possibility. For the single station located in the CHn, the carbon dioxide concentration is considerably less than in the TSw. Methane concentrations were measured onsite and are typically less than atmospheric concentration of 1.5 ppm. Five carbon-14 gas samples were collected in May at depths of 65, 92, 107, 322, and 407 m in the Pah Canyon Tuff (part of the PTn) and the TSw. A second batch of thirteen carbon-14 gas samples was collected in July from depths of 25 to 436 m, which includes the single station located in the Calico Hills Formation. Samples for carbon-13/carbon-12 analysis also were collected.

Gas sampling in USW UZ-14 was planned and ready to begin in May 1996, with the deep intervals of the Topopah Spring Tuff and the Calico Hills Formation being the principal targets for sampling. Gas sampling was planned to be performed through installation of an inflatable SEAMIST borehole liner. However, this gas sampling was postponed when it was determined that the installation of the borehole liner required a permit from the State of Nevada.

Activity 8.3.1.2.2.7.2 - Aqueous-phase chemical investigations. The objectives of this activity are to design, test, and implement methods for pore-water extraction from core samples; to obtain hydrochemical data to evaluate ground-water flow direction, flux, and residence times in the unsaturated zone at Yucca Mountain; to evaluate the extent of water-rock chemical interactions; and to model the geochemical evolution of water in the unsaturated zone.

Although large distances separate unsaturated zone boreholes, pore-water chemical compositions are similar between boreholes but vary according to the lithologic units from which they were obtained. Unsaturated zone pore water has significantly greater concentrations of chloride and dissolved solids than either saturated zone water or perched water. Waters in the Tiva Canyon Tuff, Yucca Mountain Tuff, Pah Canyon Tuff, and allocated bedded tuffs, have high concentrations of calcium sulfate or calcium chloride while water in the Calico Hills Formation has high concentrations of sodium carbonates or bicarbonate. Pore water from the Topopah Spring Tuff generally is intermediate in composition (Yang et al., in press).

Residence times of water in the Calico Hills Formation determined from carbon-14 analyses of pore-water samples indicate younger water in the northern part of Yucca Mountain and older water in the southern part.

To date, no tritium concentrations greater than 25 tritium units have been detected in pore water extracted from rock cores from boreholes USW SD-7, USW SD-9, and USW SD-12. Because of budget constraints, however, only a limited number of borehole intervals were selected for analysis, and complete profiles of each borehole were not obtained. Some high tritium concentrations (> 25 tritium units) had been expected in these boreholes because earlier studies (reported in Yang et al., in press) had detected high tritium concentrations in the PTn in boreholes UE-25 UZ#4, UE-25 UZ#5, USW NRG-6, and USW UZ-14.

Stable isotopic compositions indicate that winter precipitation is the likely source of pore water extracted from rock cores from borehole USW UZ-14 (Rousseau et al., in prep.). Based on the isotope data, the pore water underwent significant surface or shallow-depth evaporation before entering the rock matrix. In contrast, stable isotope data indicate that the perched water at USW UZ-14 underwent little or no evaporation and, therefore, must have percolated rapidly to the perched-water reservoir through fractures.

Recent analysis of a vertical profile of deuterium (δD) values for USW UZ-14 pore water indicates that water-vapor transport in Topopah Spring Tuff has not occurred. This observation supports earlier conclusions about the lack of equilibrium between the gaseous and aqueous phases in the unsaturated zone at USW UZ-1 and USW UZ-14 in Drill Hole Wash. Because gaseous-phase carbon-14 ages in the Topopah Spring Tuff are significantly older than aqueous-phase carbon-14 ages in the underlying Calico Hills Formation, rapid fracture flow seems to be the dominant aqueous transport mechanism, whereas diffusion seems to dominate the gaseous-phase system. Alternatively, the relatively young waters in the Calico Hills Formation may be the result of lateral flow from the vicinity of Solitario Canyon (Rousseau et al., in prep.).

Forecast: No additional gas sampling of surface-based boreholes is planned. Further, no additional pore-water samples will be extracted from available cores of surface-based boreholes. Pore water will be extracted from a very limited number of core samples from boreholes drilled in ESF alcoves. Work will concentrate on analyses of samples from the Ghost Dance fault alcoves. Water samples will be analyzed for cations, anions, stable isotopes, tritium, and carbon-14. A synthesis report on the hydrochemistry of the unsaturated zone will be completed using data collected from surface-based boreholes through FY 1996.

3.1.12 Study 8.3.1.2.2.8 - Fluid Flow in Unsaturated, Fractured Rock

The objective of this study is to develop and refine conceptual and numerical models describing both gas flow as well as liquid water and solute movement in unsaturated, fractured rock.

Activity 8.3.1.2.2.8.1 - Development of conceptual and numerical models of fluid flow in unsaturated fractured rock. The objective of this activity is to develop detailed conceptual and numerical models of fluid flow and transport within unsaturated, fractured rock at Yucca Mountain.

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A report (Anna, in prep.) discussing preliminary findings from three-dimensional discrete-fracture network modeling of the Tiva Canyon Tuff was submitted to DOE/YMSCO for review and acceptance. Results of the Tiva Canyon Tuff modeling were discussed in Progress Report #14.

A preliminary discrete-fracture model and analysis for the Topopah Spring Tuff is nearly complete. A box-shaped, discrete-fracture network 220 m on a side was successfully simulated. Mapped fracture orientations for the Topopah Spring Tuff, however, would not fit statistically into a spherical distribution that could be realistically simulated. Therefore, fracture orientations were "bootstrapped" (replicated) from the detailed line surveys of the ESF for Stations 10 + 78 (1078 m) to 40 + 00 (4000 m). Mapped fracture lengths from the detailed line surveys were converted into a fracture-radius distribution for use in the simulations. The Topopah Spring Tuff fracture model was calibrated by (a) statistically comparing simulated and mapped fracture intensities calculated from ESF periphery maps for each fracture subunit and from fractures that intersect traceplanes that replicate the ESF, and (b) visually comparing fracture character between the ESF periphery maps and simulated periphery-type maps. Connectivity and flow simulations were completed for four different scales (50, 100, 150, and 200 m). Connectivity analysis consisted of calculating the number of fractures and the number of pathways that are connected to the top, bottom, middle, and sides of the four flow domains. Probabilities of connection also were calculated. A transmissivity distribution for connected fractures in the Topopah Spring Tuff network was calculated using air-permeability data from boreholes USW NRG-6 and USW NRG-7a. Calculation of directional permeabilities and permeability tensors for all scales is about 50 percent complete.

A synthesis report was prepared in which models used to study flow and transport in the unsaturated zone are reviewed, and the manner in which these models have been used within the site characterization process is discussed (Zimmerman et al., 1996).

Activity 8.3.1.2.2.8.2 - Validation of conceptual and numerical models of fluid flow through unsaturated rock. The objective of this activity is to evaluate the reasonableness of the concepts on which the models developed under Activity 8.3.1.2.2.8.1 are based, by using the results of laboratory tests and tests performed in the ESF to assess the adequacy of model performances.

No progress was made during the reporting period; this was an out-year activity.

Forecast: Directional permeability and permeability tensor calculations for the Topopah Spring Tuff at scales of 50, 100, 150, and 200 m will be completed. The flow code MAFIC will be modified to simulate two-phase flow conditions through the simulated fracture network of the Topopah Spring Tuff. If possible, additional simulations for transient and tracer analysis will be completed. These results may provide significant insight on the spatial distribution of fracture flow that might occur into drifts of the proposed repository. Work will continue to determine the fractal nature of the mapped fractures from the detailed line surveys of the ESF. The study of all available mapped and simulated data will be completed. A report will be completed that

compiles results and provides interpretations of the modeled fracture geometry and flow through discrete fractures of the Topopah Spring Tuff.

3.1.13 Study 8.3.1.2.2.9 - Site Unsaturated-Zone Modeling and Synthesis

The objectives of this study are to develop appropriate conceptual models for the site unsaturated zone hydrogeologic system; to select, modify, or develop numerical hydrologic models capable of simulating the hydrogeologic system and its component subsystems; to apply the models to predict the system response to changing external and internal conditions; to evaluate the accuracy of the models using stochastic modeling, conventional statistical analyses, and sensitivity analyses; and to integrate data and analyses to synthesize a comprehensive, qualitative, and quantitative description of the site unsaturated zone hydrogeologic system under present as well as probable, or possible, future conditions. For additional details, refer to the study plan.

Locations of most of the boreholes identified in the activities in this study are shown in Figure 3-2.

Activity 8.3.1.2.2.9.1 - Conceptualization of the unsaturated-zone hydrogeologic system.

The objectives of this activity are to develop conceptual models for the overall moisture flow system within the unsaturated zone at Yucca Mountain and to develop an internally consistent set of hypotheses that describes those aspects of the site hydrogeologic system that are needed to assess the capability of the site to isolate nuclear waste for a period of 10,000 years or longer.

The primary activities for the reporting period included (a) analyzing of borehole-temperature profiles in the ESF north ramp area as a possible means of estimating percolation flux, and (b) summarizing and synthesizing site hydrologic, pneumatic, and geologic data to develop a consistent conceptual model of water and gas flow within the site unsaturated zone.

Heat fluxes from instrumented boreholes in the ESF north ramp area were analyzed using measured temperature gradients over different depth intervals. Thermal conductivities were estimated using the empirical model of Rautman (1995), which relates thermal conductivity to porosity, saturation, and temperature. At instrumented boreholes UE-25 UZ#4 and UE-25 UZ#5, located adjacent to a mapped fault in the active channel and bedrock sideslope of Pagany Wash, heat fluxes were estimated to be approximately $15 \times 10^{-3} \text{ J s}^{-1} \text{ m}^{-2}$ within the Pah Canyon Tuff. This is substantially less than the heat fluxes of 32×10^{-3} to $40 \times 10^{-3} \text{ J s}^{-1} \text{ m}^{-2}$ estimated to occur within the underlying Topopah Spring Tuff in these boreholes, using data from nearby boreholes USW UZ-1, USW NRG-6, and USW NRG-7a. The estimated difference in heat flux between the Topopah Spring Tuff and Pah Canyon Tuff was attributed to water percolating downward between the Pah Canyon Tuff and the water table. This percolation was calculated to be approximately 12 to 18 mm/yr. One-dimensional numerical modeling of temperature data from UE-25 UZ#4 and UE-25 UZ#5, using a coupled water and heat transport model, showed that the measured temperature profiles were best matched by the model using percolation fluxes of 18 mm/yr for UE-25 UZ#4 and 5 mm/yr for UE-25 UZ#5. The differences between the model

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estimates and those obtained using the analytical expression resulted because the model estimates were made over different depth intervals (downward water fluxes became more uniform with depth as a result of lateral spreading of focussed infiltration), and shallow heat fluxes are not strictly one dimensional. Other numerical simulations, using a simplified model of a wash and ridge topography, examined the factors expected to affect temperature gradients in the unsaturated zone. These factors included (a) topography, (b) the insulating effects of alluvium, (c) the occurrence of convective gas movement, and (d) the effects of water percolation. The insights gained through these simulations, along with simulated temperature profiles within the Topopah Spring Tuff in UE-25 UZ#4 and UE-25 UZ#5 using a wide range of percolation fluxes, were applied to temperature data reported by Sass et al. (1988) for other boreholes in the Drill Hole Wash area. The results of this analysis indicate that long-term percolation fluxes beneath the wash environments were about 10 mm/yr, and those beneath other topographic settings were approximately an order of magnitude less.

As discussed in Rousseau et al. (in prep.), these heat-flux-based percolation rates are considerably higher than those that have been estimated for these washes from water-balance calculations using neutron moisture-meter measurements made in shallow boreholes (Hudson and Flint, in prep.). See Section 3.1.5 (Activity 8.3.1.2.2.1.2 of this progress report). Net shallow infiltration estimated using neutron moisture-meter measurements typically varied from about 5 mm/yr beneath active channels to approximately 0 mm/yr for the adjacent alluvial terraces, with spatial variations that depended on the local thickness of the alluvium. The differences between these estimates and those obtained from the analysis of borehole temperature profiles are thought to result from differences in the time scales being reflected in the moisture-balance and temperature measurements. The neutron moisture-meter measurements reflect processes and events that are likely to be observed under present climatic conditions over a decade-long time span. Temperature measurements, by virtue of their greater depth and the longer response time associated with predominantly conductive processes, may reflect the average percolation flux over several decades or centuries. Thus, although the actual present-day percolation fluxes may differ from the values estimated on the basis of the heat-flux analysis, the latter estimates may be effective, long-term averages.

Work continued on a report (Kwicklis et al., in prep.) that summarizes the findings of many other studies on surface and subsurface hydrology, gas and aqueous chemistry, and geology in an attempt to articulate a consistent conceptual model of water and gas flow within the unsaturated zone. Although still in progress, some preliminary findings can be reported:

1. The upward vapor flux in the Topopah Spring Tuff that occurs because of vapor concentration differences caused by the geothermal gradient is about 0.005 mm/yr. Condensation and subsequent drainage at these rates is unlikely to significantly enhance percolation rates greater than about 0.05 mm/yr.
2. Mass transport of vapor by diffusion at rates of 0.005 mm/yr would result in the transport of latent heat at rates of $4.0 \times 10^{-4} \text{ J s}^{-1} \text{ m}^{-2}$, which is approximately two orders of magnitude less than the total conductive heat flux estimated for much of

Yucca Mountain. Therefore, this mechanism is unlikely to significantly affect temperature gradients in the Topopah Spring Tuff.

3. Because partial alteration to clays and zeolites has substantially reduced the permeability of many nonwelded units in the lower part of the unsaturated zone beneath Yucca Mountain, entry points for dissolved radionuclides to the saturated zone beneath Yucca Mountain may be restricted primarily to faults and other permeable zones (such as the devitrified, partially welded zones of the Prow Pass Tuff and Bullfrog Tuff) that intercept the water table. Existing maps of the geology at the water table indicate where these entry points may occur.
4. Calculations to determine the potential magnitude of the flow velocity of water diverted at a sloping interface indicate that pore-water velocity 1 km downdip from the edge of a subsurface "catchment" area could be about 1 km/yr, even if the diverted component of the flux were as little as 0.01 mm/yr.

Activity 8.3.1.2.2.9.2 - Selection, development, and testing of hydrologic-modeling computer codes. The objectives of this activity are to select, evaluate, and adapt existing numerical hydrologic-modeling codes for application to the site unsaturated zone hydrogeologic system; and to modify existing codes or develop new codes, as needed, to simulate particular problems or aspects that are unique to the Yucca Mountain system.

Several new computer codes and modules were developed for the unsaturated zone model studies. A generalized effective continuum method formulation using only one local equilibrium assumption of fractures and matrix was incorporated into the TOUGH2 simulator. This module calculates separate matrix and fracture flow at all saturations. A single-phase gas flow module was developed and incorporated into the TOUGH2 code. This module allows the user to solve the flow equation for gas, without the additional water and heat flow equations. The main utility of the "gas flow only" is for large three-dimensional, pneumatic pressure simulations. Also a three-dimensional general particle tracking module was developed for analyzing fluid flow paths and ground-water travel times using the TOUGH2 output. Finally, an additional radionuclide transport module was incorporated into TOUGH2 for the analysis of radionuclide or liquid tracer transport. This module rigorously considers three-dimensional radionuclide transport by molecular diffusion, advection, and hydrodynamic dispersion.

Activity 8.3.1.2.2.9.3 - Simulation of the natural hydrogeologic system. The objectives of this activity are to construct appropriate hydrologic models for the natural site hydrogeologic system to simulate and investigate the present state of the system, and to predict the probable future and past states of the system with regard to changes in environmental conditions.

The development of the three-dimensional site-scale model of the unsaturated zone at Yucca Mountain continued. The main activities during this period included three-dimensional model calibration and sensitivity analysis studies, and progress was made in developing the unsaturated zone model. Calibrations of the model included matching saturation and water potential data, gas pressures and flow, ambient temperature and heat flow data, perched water

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bodies, and environmental isotopes. Work has started on model calibrations with respect to percolation flux rates inferred from data about fracture coatings. Coupled calibrations of various state variables have also been started, and these show promising results in terms of constraining parameters. In addition to model calibration, considerable effort was devoted to parameter uncertainties and sensitivity studies for fracture and matrix properties, infiltration patterns, fault properties, percolation flux, and fracture and matrix heterogeneities. Also, a study was completed of the various numerical approaches (e.g., effective continuum method, dual-porosity, and dual-permeability) and appropriate uses for different processes including moisture, gas, heat, and isotope flow and transport were presented. The development of computer codes for unsaturated zone modeling continued.

A revised numerical grid for the unsaturated zone model has been developed using previous geologic models and the latest available geologic and alteration data. This updated grid contains more geologic realism and accuracy in representation, using almost 30 computational layers (see Activity 8.3.1.2.2.3.1, Section 3.1.7 of this progress report). The grid has been refined for the repository area to allow more accurate simulations of flow patterns and directions. The numerical grid used in the unsaturated zone model uses the vertical sublayering from the geologic model. The horizontal grid selection is based on many factors, including locations of boreholes, major faults, the ESF alignment, proposed boreholes, infiltration patterns, the potential repository area and locations of model boundaries. The main unsaturated zone model grid used in the FY 1996 model studies is bounded to the east by Bow Ridge fault, extends 1 km west of the Solitario Canyon fault, and extends approximately from borehole USW G-2 in the north to borehole USW G-3 in the south. This grid has about 27,000 grid blocks with about 100,000 connections for effective continuum method computations, and about 44,000 grid blocks with 165,000 connections for dual-porosity or dual-permeability calculations.

The new unsaturated zone model represents most, if not all, important processes and components of the mountain, including faults and fault offsets, perched water in appropriate locations, rock matrix and fracture properties that correspond to saturation and moisture tension data and various infiltration maps, observed temperature profiles from boreholes and fast flow paths as observed through environmental isotopes. The model was calibrated using various one- and two-dimensional submodels for individual processes, and the resulting parameter values were incorporated into the three-dimensional model. A study of various numerical approaches (e.g., effective continuum method, dual-porosity, dual-permeability, and single- versus multiple-matrix block representation, etc.) and their accuracy and efficiency in modeling different processes guided the choice of numerical method for the unsaturated zone model and submodels. The results of the study show that the effective continuum method is preferred for steady-state moisture flow and transient gas flow, whereas dual-continua methods are more appropriate for modeling transient pulses, transport, and thermal loading.

The percolation flux is a difficult parameter to determine for low flux regions such as Yucca Mountain, and unfortunately no reliable direct measurements can be made to determine this important parameter. The determination of flux relies on a combination of indirect methods involving field testing and modeling of various processes at different scales. The analysis of the available temperature and heat flow data suggest that these data may be helpful in bracketing

current values of percolation flux across the repository area. The results of the analysis indicate that the average percolation flux in the repository area is on the order of 5 mm/yr. Comparison of this analysis with three-dimensional modeling results of percolation flux at the repository horizon using the latest infiltration map by Flint et al. (in prep.) indicate similar results. The analysis indicates great heterogeneity of percolation flux over most of the potential repository area, with substantial areas of zero and low flux and substantial areas of high fluxes. The available data, however, are limited and the method of analysis has not been proven for this application. The analyses of the moisture tension and saturation data from the boreholes do not directly conflict with the average percolation flux values, but lower values are somewhat favored.

The partitioning of the percolation flux at the repository horizon into fracture and matrix components will affect the potential water flow into the drifts. Simulations using the unsaturated zone model indicate that this partitioning depends strongly on the matrix permeability of the middle nonlithophysal geologic layer in the TSw, which is the proposed repository horizon.

Three-dimensional analysis of lateral flow using the unsaturated zone model suggests that lateral flow within or around the PTn is most prevalent at relatively low infiltration/percolation flux rates. The results of the modeling show lateral flow within the PTn for several kilometers when an average low infiltration rate of about 0.1 mm/yr is applied at the ground surface. However, when the average percolation flux over the repository horizon is about 5 mm/yr, the model results predict little lateral flow. The PTn is predicted to attenuate spatial and temporal variability in the infiltration rate to some extent, but the previous conceptual model theories of large scale lateral flow within or around the PTn toward major faults is not supported by the modeling results. Most of the two-dimensional and three-dimensional simulations show lateral flow above the low permeability zeolitic rocks within the Calico Hills Formation and the Prow Pass Tuff. In addition, the temperature gradient analysis performed suggests more vertical percolation flux within the Topopah Spring Tuff than in the underlying units of the Calico Hills Formation and the Prow Pass Tuff, thereby indicating lateral flow must occur above these layers. Lateral flow above the zeolitic units is an important issue as the Project determines how much dependence should be placed on retardation and sorption due to flow through the zeolitic rocks.

Currently very limited data are available regarding the gas and moisture flow characteristics of major faults. Temperature data for USW UZ-7a, which penetrates the Ghost Dance fault, suggest that the percolation flux within the fault is less than that of the surrounding fractured porous rock. Pneumatic data indicate that most faults are permeable to gas, thereby suggesting that they are not fully saturated with water. Outside of the faults, the permeability to gas varies widely from high horizontal permeabilities within the TSw unit to relatively poor gas connectivity from the TSw to the ground surface because of attenuation within the PTn. The three-dimensional model results show relatively higher percolation rates down major faults than through the adjacent fractured rocks, especially for cases with high infiltration rates and faults with saturation-capillary pressure relationships similar to nonwelded units. In addition, for simulations using the latest infiltration map (Flint et al., in prep.) with an average rate of 4.4 mm/yr in the repository area, lateral flow within and around the PTn is small. Lateral flow beneath the repository may be large above the zeolitic units. Thus, in this instance faults are not

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expected to greatly affect moisture flow within and above the TSw, but may have much more of a role within the underlying Calico Hills and Prow Pass layers.

Chlorine-36 data and tritium data show that fast flow paths exist at Yucca Mountain because these isotopes are found in localized areas in the ESF, mostly near major structures. For example, tritium values of 80 to 150 tritium units have been measured in the Bow Ridge fault in samples obtained from a drillhole in the Bow Ridge Fault Alcove. (See Activity 8.3.1.2.2.4.7 in Section 3.1.8 of this progress report.) Analysis of these data suggest that in most instances major structures are needed to transport fluids and chemicals rapidly through the PTn unit, and that this is most efficiently done by intermittent infiltration pulses. The favored conceptual model relies on areas within washes with little alluvium cover that are intersected by faults and serve as flow concentration points for upstream watersheds (see Activity 8.3.1.2.2.1.2, Section 3.1.5 of this progress report). This conceptual model and analysis of current occurrences of chlorine-36 in the ESF indicates that chlorine-36 from weapons testing will probably be found in several areas of the ESF. Note that occurrences of chlorine-36 from weapons testing and in the ESF will not help determine the global percolation flux. Analysis of the chlorine-36 data in terms of occurrence and spreading can, at best, constrain the pulse strength required to transport the isotope to the repository level on a localized scale. The conceptual model relies on focusing of infiltrated water during storms into structural features. These pulses may be intermittent (every 10 years or so), so that they do not affect the average behavior of the mountain or its "quasi-steady state" flow patterns.

The numerical simulations of the perched water zones found that for perched water to be present these units had to have very low vertical matrix permeability (less than a micro-darcy) and little or no fracture permeability. In addition, permeability impediments that provide lateral constraints on water flow must be present, at least down dip of the expected perched water location. Rousseau et al. (in prep.) in the north ramp report use a "hypothetical fault" down dip to provide the permeability needed for perching. Recent modeling investigated the lower limit on permeability of the underlying layer needed to generate perched water under various infiltration scenarios. This permeability must be several hundreds of milli-darcies for the infiltration scenarios tested in the simulations.

A detailed east-west cross-sectional model through boreholes USW UZ-6, USW SD-7, and UE-25 UZ#16 was developed to evaluate the unsaturated zone model calibration process. The cross section was simulated using a dual-permeability formulation with the latest infiltration map (Flint et al., in prep.). Without any additional calibrations, the results showed good agreement with various data sets, including saturation and moisture tension data from USW SD-7 and UE-25 UZ#16, pneumatic data from USW SD-7 and temperature data from USW UZ-7a and USW H-3. This submodel also provided some verification of the methodology for determining the percolation flux from temperature gradient data. Finally, the submodel investigated the presence of fast flow paths using a pulse at the ground surface.

Thermal loading studies were conducted using a north-south cross section through the repository region, using both effective continuum method and dual-permeability numerical formulations. A 500-m-thick section of the saturated zone was included in the model. The

results obtained were compared with previous thermal loading studies performed without including a saturated zone in the model. The comparison showed that including the saturated zone in the model does not make a major difference, although more realistic estimates are obtained for temperature increases in the basal vitrophyre of TSw and within the Calico Hills unit. Temperature increases of some 5 to 10°C are expected at the top of the TCw and about 30°C at the water table, with the maximum temperature increase occurring about 1000 years after waste emplacement. The simulation results show that heat pipe conditions (counter current movement of liquid and vapor) prevail in the repository horizon, and complete dryout occurs when low infiltration rates (e.g., 0.1 mm/yr) are used. For higher infiltration rates (e.g., 4.4 mm/yr) no complete dryout occurs because the estimated percolation flux is greater than the amount of energy available to vaporize the moisture. This result is very important because it implies 100 percent humidity will occur; and, as a result, corrosion rates would be expected to increase. The effective continuum method and dual-permeability formulations showed similar results for many aspects of thermal loading, but differed mainly in the extent of the boiling zone and the transient water flow rates through the repository.

A dual-permeability simulation using the three-dimensional unsaturated zone model with a climate change was conducted. The current spatially variable infiltration rates were assumed to increase by a factor of three. The impact on moisture flow within the mountain was then evaluated. The results showed that the pulse moved rapidly through the system and in many locations reached the water table in less than 1000 years. Localized fast paths allow movement through the unsaturated zone in tens of years down to the water table. The major barriers to the vertical flow are the zeolitic units in the Calico Hills Formation and Prow Pass Tuff. These barriers enhance recharge to the perched water bodies. Rapid fracture flow occurs through the repository horizon. The system reaches steady state after about 30000 years.

Forecast: Work will continue on modifying the three-dimensional model grid by extending the model area to the north of USW G-2 to investigate the high potentiometric surface gradient effects and potential perched water bodies. Modeling studies will continue for predicting fluid and heat flow and distribution at Yucca Mountain, including (a) incorporating updated, distributed matrix/fracture rock properties; (b) refining geological models for different hydrogeologic units; (c) conducting further comprehensive studies to determine percolation fluxes using field observations of saturation, moisture tension and temperature data, combined with direct and inverse modeling analysis; (d) performing comparative studies of model predictions and field observations regarding percolation fluxes, saturations, and moisture tensions and lateral movement; and (e) investigating effects of faults, thermal loading, and air circulation on moisture movement within Yucca Mountain.

Work will proceed on the perched water analyses using the newest infiltration map and localized refined meshes around the perched water bodies. Additional thermal modeling studies will be performed using the three-dimensional site-scale model grid to evaluate the effects of thermal loading and three-dimensional geologic features, such as faults, on the ambient moisture, gas, and heat flow in Yucca Mountain.

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A report (Kwicklis et al., in prep.) will summarize the findings of many other studies on surface and subsurface hydrology, gas and aqueous chemistry, and geology in an attempt to articulate a consistent conceptual model of water and gas flow within the unsaturated zone.

3.1.14 Study 8.3.1.2.3.1 - Characterization of the Site Saturated-Zone Ground-Water Flow System

The objectives of this study are to determine the internal and external boundary conditions and parameters that can be applied to the site saturated-zone flow and transport models, and determine the rates and directions of ground-water flow.

Locations of most of the boreholes identified in the activities included in this study are shown in Figure 3-2.

Activity 8.3.1.2.3.1.1 - Solitario Canyon fault study in the saturated zone. The objectives of this activity are to characterize the hydrologic nature, significance, and implications of the Solitario Canyon fault, as well as to determine if the fault is a barrier to eastward flow of water in the saturated zone beneath the repository block.

No progress was made during the reporting period; this was an out-year activity.

Activity 8.3.1.2.3.1.2 - Site potentiometric-level evaluation. The objectives of this activity are to analyze the character and magnitudes of potentiometric-level fluctuations with depth and time to estimate transmissive and storage properties, to determine hydraulic gradient, to define altitude distribution of uppermost potentiometric surface, to determine long-term water-level trends, and to determine the water-level response to nearby pumping.

Routine monitoring of water levels in the saturated zone at Yucca Mountain continued. Quarterly or more frequent water-level measurements were made in 22 wells that monitored 28 intervals. Hourly water-level data were collected from two wells that monitored three intervals. Two zones in well USW H-5 were monitored continuously to detect water-level fluctuations caused by earthquakes. A review of the continuous record indicated that there were no major earthquake-related water-level fluctuations during this reporting period. Additional water-level measurements were made in support of activities at the C-hole complex by installing transducers in wells UE-25 WT#3, UE-25 WT#14, and USW H-4 in addition to the transducer already installed in well UE-25 p#1. Water levels are recorded in these wells every 60 minutes. Monthly and hourly water levels for 1995 were reviewed and submitted to the Records Processing Center. Water levels have remained essentially stable during this reporting period.

Testing conducted in well USW G-2 is reported under Activity 8.3.1.2.1.3.2, discussed in Section 3.1.3 of this progress report.

Several USGS Open-File and Water-Resources Investigations reports were published. These reports describe water levels measured from 1990 through 1993 and describe the

potentiometric surface near Yucca Mountain (Tucci et al., 1996; Tucci and Burkhardt, 1995). Graves et al. (1996) describes water levels for 1994.

Work is nearing completion on a synthesis report of water-level data for 1985 through 1995. The report (Graves et al., in prep.) presents monthly data in both tabular and graphical form for 36 intervals in 28 wells. The presentation of 11 years of data shows some minor trends that cannot be seen in the annual data. Work also is nearing completion on a report (O'Brien, in press) that analyzes hydraulic tests in the saturated zone in wells USW WT-10 and UE-25 WT#12 and the tests performed in a perched water body in USW SD-7. Results indicated that USW WT-10 tapped the aquifer in an extremely transmissive area while UE-25 WT#12 appeared to be poorly connected to the aquifer.

Activity 8.3.1.2.3.1.3 - Analysis of single- and multiple-well hydraulic stress tests. The objectives of this activity are to determine intraborehole flow profiles for each well at the UE-25 (C-hole) well complex under static and pumping conditions, to correlate intraborehole flow rates with lithology and fractures, to identify test-scale hydrologic boundaries, and to estimate aquifer properties (e.g., transmissivity and storage coefficient).

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.2.3.1.4 - Multiple-well interference testing. The objectives of this activity are to discriminate between equivalent-porous-medium and fracture-network models at the scale of the tests, to determine effective aquifer properties (e.g., transmissivity and storage coefficient), and to evaluate the three-dimensional nature of the flow field in the test vicinity.

In February 1996, a hydraulic test was initiated in the Lower Bullfrog and Tram zones at the C-hole complex. Well UE-25 c#3 was pumped, and wells UE-25 c#1 and UE-25 c#2 were used as observation wells. The discharge varied from 131 to 139 gallons (439 to 526 L) per minute. The water level in the pumped zone was drawn down approximately 9 ft (2.7 m), and the maximum drawdown in the observation wells was less than 1 ft (0.3 m). Approximately 7000 minutes of data were acquired before tracer injection was started; this period constitutes the analyzable record and was sufficient to calculate hydraulic parameters. Analysis of the drawdown and recovery data has begun, and initial estimates of transmissivity, hydraulic conductivity, and storativity have been made.

In May 1996, a hydraulic test was initiated in the Lower Bullfrog zone. Well UE-25 c#3 was the pumped well, and wells UE-25 c#1 and UE-25 c#2 were used as observation wells. The discharge varied from 151 to 156 gallons (572 to 591 L) per minute. The water level in the pumped zone was drawn down approximately 17 ft (5.2 m), and the maximum drawdown in zones in the observation wells was approximately 1.5 ft (0.4 m). Approximately 7500 minutes of data were acquired before tracer testing was started; this period constitutes the analyzable record and was sufficient to calculate hydraulic parameters. Analysis of the drawdown and recovery data from this test has begun, and initial estimates of transmissivity, hydraulic conductivity, and storativity have been made.

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During June 1996, a computer program was written to automate the process of correlating the hydraulic pressure in the packed-off intervals of the C-hole complex with progressively lagged barometric pressures under nonpumping conditions. At the optimal lag, which indicates the time needed for barometric-pressure fluctuations at the surface to reach the packed-off interval, the correlation is at a maximum, and an optimal barometric efficiency of the packed-off interval is calculated. This value is used to correct the record during pumping intervals for barometric-pressure effects. This program and others were used to implement analytical (nonnumeric) porous-medium solutions for interpreting hydraulic drawdown and recovery data acquired during hydraulic tests.

Geldon (1996) discusses tests conducted at the C-hole complex in 1984. Fahy et al., (in prep.) describes the June 1995 hydraulic test.

Activity 8.3.1.2.3.1.5 - Testing of the C-hole sites with conservative tracers. The objectives of this activity are to determine aquifer transport properties, to evaluate applicability of equivalent-porous-medium models to analyze tracer tests, and to evaluate spatial correlation and scale-dependency of transport parameters.

In February 1996, a conservative tracer test was initiated in the Lower Bullfrog and Tram zones at the C-hole complex following completion of the hydraulic test and after a quasi-steady state flow field had been established. Well UE-25 c#3 was pumped, and UE-25 c#2 was used as the injection well. Sodium iodide was used as the tracer, and iodide concentration was determined in the pumped water. The discharge progressively decreased from 136 gallons (515 L) per minute initially to 98 gallons (371 L) per minute at the end of the test approximately 6 weeks later; this was caused by a failing pump. Tracer breakthrough occurred after approximately 5 days and reached peak concentration approximately 18 days after injection. The test ended 45 days after injection with tracer concentration still ten times the detection limit.

Both pumping and tracer injection were in a 600-ft (183 m) thick zone, extending from a depth of 2300 ft (701 m) to 2900 ft (884 m) below land surface in the lower-Bullfrog - upper-Tram geohydrologic interval (Geldon, 1996) of the Crater Flat Group. This is the most conductive interval at the complex, with a transmissivity value of 18,000 to 24,000 ft²/day (1672 - 2223 m²/day), based on the February 1996 aquifer test.

Analysis of the breakthrough curve has begun, and some initial estimates have been made for the porosity, dispersivity, and diffusive characteristics for the unit. During June 1996, a module was added to the computer program (discussed under Activity 8.3.1.2.3.1.4) to implement the Moench (1995) porous medium solution to analyze convergent tracer test results obtained from the February-March tracer test.

Activity 8.3.1.2.3.1.6 - Well testing with conservative tracers throughout the site. The objectives of this activity are to determine aquifer transport properties at selected site locations; to evaluate vertical and horizontal spatial variability of flow parameters; and to examine spatial correlation, cross correlation, and scale dependency of flow and transport parameters.

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No progress was made during the reporting period; this was an out-year activity.

Activity 8.3.1.2.3.1.7 - Testing of the C-hole sites with reactive tracers. The objective of this activity is to characterize the chemical and physical properties of the geologic media in the saturated zone in the vicinity of the C-holes that will affect radionuclide retardation during ground water flow within the saturated zone.

Project hydrologists conducted two conservative tracer tests to determine (a) which hole, UE-25 c#1 or UE-25 c#2, would better serve as an injection well for a reactive tracer test and (b) what mass of lithium bromide (with lithium as the reactive tracer) would be needed to conduct a successful reactive tracer test. It was concluded that UE-25 c#2 is the preferred injection well, and at least 80 to 90 kg of lithium bromide will be necessary to conduct a successful reactive tracer test.

Both conservative tracer tests were conducted in an approximately 300-ft (91.4-m) packed-off interval in the Bullfrog Tuff extending from approximately 2300 to 2600 ft (701 to 792 m) below surface or 1000 to 1300 ft (305 to 396 m) below the water table in the C-holes. This interval has the largest hydraulic conductivity of any major zone in the C-holes (see Activity 8.3.1.2.3.1.5). UE-25 c#3 was used as the production well in both tracer tests, with the production rate remaining nearly constant at ~154 gallons (583 L) per minute. The first tracer test involved the injection of approximately 10 kg of pentafluorobenzoic acid into UE-25 c#2. The second tracer test, involved the injection of approximately 12.7 kg of iodide (as ~15 kg of sodium iodide) into UE-25 c#1. Both tests were conducted under partial recirculation conditions, with 4 to 5 gallons (15 to 19 L) per minute being recirculated from the UE-25 c#3 discharge into either UE-25 c#1 or UE-25 c#2. The partial recirculation was established at least a day before the tracers were injected and maintained for at least 16 days after injection. The test conditions in the two tracer tests are summarized in Table 3-6.

A summary of the tracer test results as of August 27, 1996, is provided in Table 3-7.

The pentafluorobenzoic acid data have been analyzed using a Laplace transform transfer function model to estimate transport parameters by "fitting" the data. However, the results have been inconclusive since analysis of a single tracer breakthrough curve is ambiguous because it is not possible to distinguish between matrix diffusion and slow release of tracer from the injection wellbore. Both processes can result in the long tail observed in the pentafluorobenzoic acid breakthrough curve, and a reasonable fit to the data can be obtained by assuming any amount of matrix diffusion, including none. Matrix diffusion can be determined only by simultaneously injecting conservative tracers with different diffusion coefficients. This will be a feature of the upcoming reactive tracer test. Details of the tracer test results and interpretative analyses are provided in a report (Reimus and Turin, in prep.).

Several laboratory tests were also conducted during this reporting period, including (a) batch sorption tests to determine lithium sorption to corrosion products from the UE-25 c#3 packer string, (b) batch sorption tests to determine sorption of various potential reactive tracers other than lithium to Bullfrog Tuff, and (c) visualization experiments intended to simulate

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Table 3-6. Test Conditions for the Pentafluorobenzoic Acid and Iodide Tracer Tests

Test Parameter	Pentafluorobenzoic Acid Test	Iodide Test
UE-25 c#3 production flow rate	~154 gpm (583 L/m)	~154 gpm (583 L/m)
Injection well	UE-25 c#2	UE-25 c#1
Injection mass	~10 kg	~15 kg NaI or 12.7 kg I
Injection concentration	~10 g/L (~1000 L)	~15 g/L (~1000 L)
Date, time of injection	5/15/96, 12:20 pm	6/18/96, 8:00 am
Recirculation flow rate	5.3 gpm* (20.1 L/m)	3.8 - 4.0 gpm* (14.4-15.1 L/m)
Recirculation duration (after injection)	23 days	16 days
Head increase in injection interval due to recirculation	-0-	~1 ft (0.3 m) H ₂ O

*Determined from volumetric calibrations of progressing-cavity pump discharge as a function of back pressure.

Table 3-7. Summary Information on Tracer Recoveries and Water Volumes from C-Hole Tests

Item	Result
Percentage pentafluorobenzoic acid recovery	70 ± 2
Percentage iodide recovery from UE-25 c#1 injection	2 ± 1
Iodide mass recovered from USGS injection into UE-25 c#2 since May 8	1.25 kg ± 150g
Water volume produced from UE-25 c#3	~24.5 million gallons (92.7 million L)
Water volume reinjected into UE-25 c#2	~275,000 gallons (1.04 million L)
Water volume reinjected into UE-25 c#1	~90,000 gallons (340,687 L)
Mass of pentafluorobenzoic acid reinjected into either UE-25 c#1 or UE-25 c#2	~170 g or 1.7% of original mass
Mass of iodide reinjected into either UE-25 c#1 or UE-25 c#2	<20 g

injection of dense tracer solutions into boreholes to investigate the potential for significant delay of the tracer in the wellbore caused by density effects. The principal conclusions of these studies were (a) lithium sorption to iron corrosion products on the C-hole packer strings is not great enough to significantly affect the results of reactive tracer tests in the field, (b) Rhodamine-WT (an orange-red fluorescent dye tracer) appears to be the most promising of several potential reactive tracers that were tested for sorption to Bullfrog Tuff for use as an alternative to lithium in field tests, and (c) a significant amount of the injected tracer solution in the field tests may have sunk to the bottom of the packed-off zones (even with partial recirculation) because of the greater density of the injectate relative to the ground water. A report describing these laboratory results is being prepared (Reimus and Turin, in prep.).

Activity 8.3.1.2.3.1.8 - Well testing with reactive tracers throughout the site. The objective of this activity is to characterize chemical and physical properties of the geologic media in the saturated zone throughout the site that will affect radionuclide retardation during ground-water flow within the saturated zone.

No progress was made during the reporting period; this was an out-year activity.

Forecast: Quarterly water-level monitoring will continue as part of the potentiometric-level evaluation; hourly and continuous monitoring will be discontinued. The results of water-level monitoring in 1994 will be published as will the synthesis of data for 1985-1995. The results of monitoring in 1995 will be submitted for approval for release as a USGS Open-File Report. No additional hydraulic tests in the water table series wells have been funded nor has the analysis of the tests in well USW G-2 been funded. Planned activities at the C-hole complex include additional conservative and reactive tracer tests.

Reactive tracer tests involving lithium bromide, polystyrene/silica microspheres, and possibly a fluorinated benzoic acid (conservative tracer) will be conducted in the saturated zone at the C-holes. Laboratory experiments will be conducted to assess the transport of lithium and other potential reactive tracers in artificially fractured cores from the C-holes and to measure the diffusion coefficients of various tracers used in the C-holes in relevant tuff matrices (from C-hole cores). In conjunction with these experiments, batch sorption and crushed tuff column transport experiments will be conducted to establish sorption parameters and to assess the applicability of these sorption parameters to fracture transport. The information derived from reactive tracer tests at the C-holes and from the supporting laboratory experiments will be integrated into the site saturated zone transport model.

3.1.15 Study 8.3.1.2.3.2 - Characterization of the Saturated-Zone Hydrochemistry

The objective of this study is to describe the composition of, and spatial compositional variations in, saturated zone ground waters using new and extant data; to identify the chemical and physical processes that influence ground-water chemistry; and to aid in the identification and quantification of fluxes to, from, and within the saturated zone.

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Activity 8.3.1.2.3.2.1 - Assessment of saturated-zone hydrochemical data availability and needs. The objectives of this activity are to compile and evaluate extant hydrochemical data for the saturated zone, to identify data deficiencies and potential sampling sites and assemble requisite material for sample and field data collection, and to augment extant information by collecting and analyzing new hydrochemical samples and data.

The activity was completed with publication of the report (Perfect et al., 1995) on the compilation and assessment of data within the region.

Activity 8.3.1.2.3.2.2 - Hydrochemical characterization of water in the upper part of the saturated zone. The objectives of this activity are to describe the hydrochemistry of the upper part of the saturated zone by collecting representative water samples from intervals within the upper 100 m of the saturated zone, within and adjacent to the site area, and studying their chemical and isotopic compositions; and to estimate flux to or from the saturated zone by collecting interstitial water and gas samples from immediately above the water table and studying their chemical and isotopic compositions.

Compilation of data collected during FY 1995 and earlier years was begun. The data were organized in a spreadsheet and were to be submitted to the records system. However, this process was not completed before funds were exhausted early in the reporting period. Collection of additional data in FY 1996 was not funded.

Activity 8.3.1.2.3.2.3 - Regional hydrochemical tests and analyses. The objective of this activity is to describe regional spatial variations in ground-water chemistry in the saturated zone by collecting representative water samples from wells and springs within the region and by studying their chemical and isotopic compositions.

A report (Steinkampf and Werrell, in prep.) describes sample collection, hydrochemical data, and data interpretation from samples collected in Death Valley National Monument.

Activity 8.3.1.2.3.2.4 - Synthesis of saturated-zone hydrochemistry. The objectives of this study are to describe the saturated zone hydrochemistry; to identify chemical and physical processes that influence ground-water chemistry; and to aid in the identification and/or quantification of ground-water travel times, climatic conditions during periods of recharge, flowpaths, and fluxes to, from, and within the saturated zone.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: The Death Valley hydrochemistry report will be completed pending availability of funds. The summary of site-area and vicinity saturated zone hydrochemical data will be completed under the same conditions. However, at the time this progress report was being prepared, no funding was expected for FY 1997 for any saturated zone hydrochemical activities.

3.1.16 Study 8.3.1.2.3.3 - Saturated-Zone Hydrologic System Synthesis and Modeling

The objectives of this study are to synthesize the available data into a model and make a qualitative analysis of how the system is functioning and to represent quantitative observations of hydrogeologic data pertaining to the ground-water flow system in a comprehensive flow model.

Locations of most boreholes identified in the activities comprising this study are shown in Figure 3-2.

Activity 8.3.1.2.3.3.1 - Conceptualization of saturated zone flow models within the boundaries of the accessible environment. The objectives of this study are to synthesize the available hydrogeologic data to develop a conceptual model and to make a qualitative analysis of how the site saturated zone hydrogeologic system is functioning.

A report describing the conceptual model of the saturated zone flow system (Luckey et al., 1996) was revised and will be published soon.

The three-dimensional, saturated zone hydrogeologic framework model construction was essentially completed, and the model was reviewed. The framework model, which contained 16 geohydrologic units, covered the area bounded by latitude 36°N and 37°15' N and longitude 116°W and 117°W. The model had horizontal gridding of 1500 m by 1500 m and was used to construct the flow model. The framework model was constructed using techniques described by Faunt (1994).

Work continued on estimating hydraulic parameters based on analysis of new single-well aquifer-test data obtained from wells USW WT-10, UE-25 WT#12 (O'Brien, in press) and USW G-2. The compilation of available hydraulic parameters for the site model area into a comprehensive spreadsheet was nearly complete.

The construction of the preliminary site saturated zone model continued using the FEHMN code (Zyvoloski et al., 1995a). Several finite-element meshes were constructed. The initial meshes were based on the regional hydrogeologic framework model, and later meshes were based on the site hydrogeologic framework model. The meshes were constructed using the GEOMESH software (Gable et al., 1995). All meshes included nodes corresponding to water-level observation points in wells. Near the end of the reporting period, the mesh contained 24,877 nodes and 135,599 tetrahedral elements. The complexity of the grid was reduced by eliminating nodes that previously represented zero-thickness layers. This modification substantially improved model running times. Preliminary calibration runs with the FEHMN code were conducted, but the model simulation has not yet duplicated the natural system. A letter report documenting the status of the model as of August 1996 was completed. A proceedings paper documenting the development of the site saturated-zone flow model was presented (Czarnecki et al., 1996) at Model CARE '96 in Golden, Colorado.

Activity 8.3.1.2.3.3.2 - Development of fracture network model. The objectives of this activity are to relate results of hydraulic and conservative tracer tests in wells to fracture-network

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flow characteristics at Yucca Mountain, to develop methods to analyze hydrologic data to determine fractured rock flow characteristics, and to model flow in the saturated zone in the vicinity of C-holes.

A report (Cohen et al., 1996) describes construction and results of a numerical model used to test the potential effects of the faulted structure in the saturated units on flow geometry and mixing. The region modeled corresponds to a cross section approximately 1 km below the water table and 2.2 km wide. Geologic units and faults are modeled. Simulations show that fault displacements can produce significant upward and downward fluxes, even without the presence of highly permeable faults or flow sources from the Paleozoic units. Inclusion of geothermal heating and potential fluid upwelling from the Paleozoic aquifer is now being considered.

The report includes a discussion of the use of the cluster variable aperture annealing inversion algorithm to invert a known permeability distribution, thereby validating the usefulness of the routine. A preliminary result of the inversion of the June 1995 pump test data collected during C-hole pumping was presented to illustrate a three-dimensional inversion of field data.

The report also includes a discussion of issues regarding tracer tests in a fractured rock mass. The discussion addresses problems associated with time and spatial scales, flow geometry, knowledge of the source term, and the limitation of the advection-dispersion equation. Recommendations are given regarding future hydrologic tests.

Activity 8.3.1.2.3.3.3 - Calculation of flow paths, fluxes, and velocities within the saturated zone to the accessible environment. The objectives of this activity are to estimate ground-water flow direction and magnitude for input into travel-time calculations; and to evaluate the porous-media concept and fracture-network concept for determining flow paths, fluxes, and velocities.

No progress was made during the reporting period; this was an out-year activity.

Forecast: Construction and calibration of the preliminary site saturated-zone flow model will continue, using the site hydrogeologic framework model. The framework model will be updated as appropriate. A report documenting the status of the calibration of the flow model will be prepared and submitted for review in FY 1997. The report documenting the conceptual model of the site saturated zone hydrology will be completed.

The two-dimensional (cross-sectional) saturated zone model will be expanded to three dimensions. The modeled region is subsite scale and considers the area enclosing the potential repository, the Solitario Canyon fault, and the area and prominent faults immediately downgradient from the repository. The model will be developed as a tool to test hypotheses of the saturated zone processes in the immediate site area, and to understand mixing processes in the presence of the faulted, stratified rock mass that is subjected to geothermal heating and potential upwelling of fluids from depth. The model will consider a region much smaller than the current site-scale saturated zone model, enabling evaluation of local processes and observation of flow geometry and hence mixing. Geologic, hydrologic, and water chemistry data

will be used to develop and calibrate the model. The model will be applied to the design and analysis of future saturated zone hydrologic tests.

3.1.17 Related International Hydrological Work

No progress occurred during the reporting period. As of November 8, 1995, the subsidiary agreements under which the cooperative work had been conducted were terminated and all international collaboration was discontinued.

The OCRWM had bilateral and technical cooperative agreements with Canada (Atomic Energy of Canada Limited [AECL]), Switzerland (Swiss National Cooperative for the Storage of Radioactive Waste [Nagra]), and Sweden (Swedish Nuclear Fuel and Waste Management Company [SKB]) and has participated in activities of international organizations such as the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the Commission of European Communities (CEC).

3.2 GEOCHEMISTRY (SCP SECTION 8.3.1.3)

The changes to the Geochemistry Program since the SCP was issued are summarized in Appendix A, Section A.1.2.

3.2.1 Study 8.3.1.3.1.1 - Ground-Water Chemistry Model

The objective of this study is to develop a ground-water chemistry model that will initially describe pre-emplacement conditions. Future changes in these conditions may then be considered, including those resulting from changes in infiltration rates as influenced by climatic conditions; long-term mineralogic changes, particularly those influenced by the thermal pulse from emplaced waste; and changes caused by the emplaced waste, engineered materials emplaced in the repository (e.g., concrete) and possible igneous activity.

A description of a conceptual model of ground-water chemistry was incorporated into a larger report on radionuclide retardation studies at Yucca Mountain (Triay et al., in prep.).

The main conclusions presented in the chapter on the conceptual model of ground-water chemistry are as follows:

- Chemical compositions of pore waters, perched waters, and saturated zone ground waters suggest there are basically two types of waters in Yucca Mountain.

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- Type one water occurs as pore water in units above and below the Calico Hills Formation. This water type generally has higher ionic strength than type two water and is strongly influenced by soil zone processes such as the precipitation of calcite, gypsum, and silica.
- Type two water occurs as perched water and saturated zone ground water. This water type is more dilute than type one water and is strongly influenced by hydrolysis reactions involving carbonic acid.
- Pore water in the Calico Hills Formation appear to be mixtures of the two basic water types (i.e., pore water from the overlying Topopah Spring Tuff and perched water).
- The chemical data indicate that equilibration of pore water and perched or ground water is a very slow process.
- Future compositional variations in water chemistry under ambient conditions are likely to be minor.
- The UE-25 J#13 and UE-25 p#1 water compositions appear to bound most of the compositional variations expected in the ambient flow system at Yucca Mountain in the future. The main parameters not entirely bounded by these compositions are pH, Eh, and chloride concentrations.
- The uncertainty in the identity of alteration phases that control the type two water compositions and the lack of experimental data on the kinetics of formation of possible alteration phases preclude the development of realistic quantitative models of water chemistry in Yucca Mountain.

Forecast: Further work on this study has been deferred because of lack of funding.

3.2.2 Study 8.3.1.3.2.1 - Mineralogy, Petrology, and Chemistry of Transport Pathways

The objectives of this study are to determine the three-dimensional distribution of mineral types, compositions, abundances, and petrographic textures within the potential host rock; and to determine the three-dimensional distribution of mineral types, composition, and abundances in rocks beyond the host rock that provide pathways to the accessible environment.

The three-volume summary and synthesis report on mineralogy and petrology studies of Yucca Mountain (Bish et al., in prep.) documents the results of a comprehensive set of studies. The contents of the individual report volumes are described in Sections 3.2.2, 3.2.3 and 3.2.4 of this progress report. A brief description of the key findings to date is provided below.

From the studies described in the summary and synthesis report on mineralogy and petrology of Yucca Mountain (Bish et al., in prep.) and supporting the development of the three-

dimensional mineralogy model, the Project now has a catalog of the potentially hazardous minerals occurring at Yucca Mountain. Data from recent microautoradiography experiments has linked Yucca Mountain mineralogy to transport retardation processes. All identified hydrothermal alteration in the unsaturated zone is of Tertiary age; there is no evidence of recent or ongoing hydrothermal activity, and no evidence of hydrothermal eruption breccias of any age has been found. Calcite-silica deposits have been shown to be of surficial pedogenic origin. The static water level has not reached the elevation of the potential repository during the last 11 million years. During natural alteration under saturated conditions, clinoptilolite transformed to analcime at temperatures of about 100°C. Under ambient conditions, clinoptilolite below the potential repository will not recrystallize within 10^5 yr; therefore the sorptive capacity will be available to retard radionuclides released from the repository.

The expected products of repository-induced alteration are smectite, clinoptilolite and possibly other zeolites, opal-cristobalite-tridymite, and possibly other silica materials. Silica colloids, generated by repository-induced alteration, may sorb actinides but are not expected to travel far into the vitrophyre below the potential repository. Dehydration of vitrophyre glass may release as much as the equivalent of an 84-cm column of water, although the extent of such dehydration will depend on the partial pressure of water.

An equation of state for clinoptilolite was developed that, for the first time, allows calculation of the clinoptilolite water content as a function of temperature, pressure, and exchangeable cation composition. The equation of state was implemented in quantitative models to illustrate the potential effects of hydration and dehydration processes on heat and water budgets. Although detailed calculations with a complete code are necessary (e.g., FEHM), the preliminary results show that the amount of water released from clinoptilolite is comparable to thousands of years of infiltration, and clinoptilolite dehydration could consume tens of years of thermal energy generated by radioactive waste. The stability of clinoptilolite continues to be an important issue with respect to permeability and radionuclide sorption (especially neptunium). Detailed modeling using estimated thermodynamic data shows that the activity of silica (or the presence of various silica polymorphs) is a key variable in the persistence of clinoptilolite. Thermodynamic data are still too limited to permit an accurate determination of the fate of clinoptilolite. However, significant progress has been made in understanding the kinetics of the transformation of zeolites and the silica polymorphs.

Activity 8.3.1.3.2.1.1 - Petrologic stratigraphy of the Topopah Spring Tuff. The objective of this activity is to determine the petrologic variability within the devitrified Topopah Spring Tuff at Yucca Mountain and to define the stratigraphic distribution of variability.

Studies of the textural stratigraphy of the potential host rock, the rhyolitic Topopah Spring Tuff, were summarized and incorporated into volume I of a summary and synthesis report on mineralogy and petrology studies (Bish et al., in prep.). The chemistry of the potential host rock is generally homogeneous but mineralogy and texture vary. Preliminary data suggest that ratios of quartz to tridymite plus cristobalite can be used to quantify lithophysal character within the chemically homogeneous host rock. Although the potential host rock is chemically homogeneous in most respects, there is substantial evidence of increased calcium and magnesium

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contents caused by minor zeolitization or presence of surface weathering products. The presence of zeolites or surface weathering products may result in a mineralogic and geochemical environment having features significantly different than those indicated by presently available data. The alternative mineralogic and geochemical features could impact evaluations of repository performance.

Activity 8.3.1.3.2.1.2 - Mineral distributions between the host rock and the accessible environment. The objective of this activity is to determine the three-dimensional distribution, chemistry, and total abundance of all major rock-matrix minerals, between the host rock and the accessible environment. The analysis of the three-dimensional stratigraphy will be most heavily weighted toward those units that will first be encountered along potential flow paths away from the repository (i.e., Calico Hills Formation).

Data collection was completed and a letter report describes zeolite abundances and the vitric-to-zeolitic transition in drillholes USW SD-7, USW SD-9, and USW SD-12 at Yucca Mountain (Chipera et al., 1996a). This report evaluates quantitative x-ray diffraction mineralogic data collected for samples representing the unsaturated zone interval from the basal vitrophyre of the Topopah Spring Tuff to the water table in drillholes USW SD-7, USW SD-9, and USW SD-12. In addition, x-ray fluorescence chemical data have been collected from selected samples from USW SD-12. The x-ray fluorescence data are being used to improve the quantitative determinations of mineral abundances. These data span the vitric-to-zeolitic transition and provides new information for the central and southern part of the potential repository area at Yucca Mountain. Close sample spacing for x-ray diffraction data from this interval in these three holes provide a detailed determination of mineral stratigraphy, particularly for the transition between vitric intervals and zeolitic tuff. Unexpected results include recognition of (a) the occurrence of chabazite in the vitric zone of USW SD-7, (b) a broad overlap of vitric and zeolitic horizons (over vertical ranges up to 70 m), and (c) the importance of the informally defined bedded tuffs beneath the Calico Hills Formation as a subunit with generally more extensive zeolitization than the Calico Hills Formation in the southern part of the potential repository area. The zeolitized unit identified in item (c) contains up to 60 percent clinoptilolite and may be present above or below the water table. The unit appears to have been more porous, and therefore more readily altered to zeolite, than other stratigraphic units in the Yucca Mountain area, and may constitute a significant natural barrier to radionuclide transport. Geopetal features (which identify original top or bottom of the horizon) indicate a pre-Rainier Mesa (~10 Ma) age of zeolitization. Combined with geochemical data, the data from the zeolitic horizons record a long history (>10 Ma) of retardation of strontium transport, although the data suggest that simplistic models of one-dimensional flow are inadequate. Complex interstratification of zeolites and glass, with highly variable profiles between drill cores, point to remaining problems in constructing detailed mineral stratigraphies but provide important information for constructing bounded models of zeolite stratigraphy for transport calculations.

A paper (Vaniman et al., 1996) was published that describes the use of microautoradiography to evaluate the mineralogic basis of Pu(V) retention by tuffs from Yucca Mountain. Altered orthopyroxenes and oxide minerals are associated with high plutonium retention, but these minerals are limited to specific stratigraphic horizons. A weaker but more general

association of plutonium with smectite occurs in most samples. Thin sections that cross fractures allow comparative studies of plutonium retention by minerals composing fracture linings versus matrix minerals. Use of silver metal in emulsions as a measure of underlying plutonium concentration in electron-microprobe analysis can quantify plutonium retention along fracture walls and provide mineral to mineral plutonium retention factors. For smectite-lined microfractures in zeolitized tuff, the smectite/clinoptilolite plutonium retention factor is >80 . The clinoptilolite K_d s for plutonium are relatively low and are expected to be somewhat higher than those for neptunium, which is about 2 to 3 for clinoptilolite in tuffaceous aquifer water. This retention factor is related to K_d data that can be obtained from crushed-tuff and solid wafer experiments, but the relationship is complicated by the sample geometry (e.g., the distribution of smectite along fractures) and the sensitivity of smectite sorptive behavior to water-rock ratios.

Volume I of a summary and synthesis report on mineralogy and petrology studies at Yucca Mountain (Bish et al., in prep.) was completed, and it summarizes studies on this topic since 1980. More than 1300 samples from Yucca Mountain have been analyzed for quantitative mineralogy and interpreted in the context of stratigraphic position. The data obtained allow the mineralogy of Yucca Mountain to be assessed in terms of its geologic and hydrologic setting and in terms of the potential for minerals at the mountain to retard radionuclide migration.

Quantitative data on mineral abundances can be summarized in terms of the three major mineral-stratigraphic units (vitric, devitrified, and zeolitic layers) used in constructing a three-dimensional mineralogical model of Yucca Mountain. The interpretive bounds of these models can be defined by separate visualizations that represent medial, maximal, and minimal thicknesses of zeolitic horizons that play a role in transport calculations. Particular attention is given to the Calico Hills Formation and its boundary units, where the complexity of the vitric-to-zeolitic transition leads to large differences between the medial and maximal zeolite stratigraphic models. These three models of zeolite stratigraphy (medial, maximal, and minimal) provide not only bounds for visualizations of the site's mineral stratigraphy, but also are adaptable for different radionuclides (i.e., a highly sorbing nuclide such as strontium may be significantly retained on only partially zeolitized rocks and therefore the maximal model is most applicable, whereas poorly sorbing neptunium species may experience retardation only where the rocks are predominantly zeolitic and a minimal model would be appropriate).

All minerals of potential importance for radionuclide retardation can be described in terms of their potentials for sorption, surface complexation, or coprecipitation in terms of ideal end-member properties that are complicated by the geochemical environment. Mineral chemistry, particularly of calcite, can be used as a natural self-analog to define the transport ranges over which retardation is effective at the site; retardation effects are generally evident within just a few tens of meters of transport. Results of laboratory sorption studies, including microautoradiography, show that both major minerals (zeolites) and minor or trace minerals (smectites, manganese-oxides, and amorphous iron-manganese-rich alteration products) are particularly important and complementary in retarding radionuclide transport. These important minerals are often concentrated in fractures, particularly in fractures of known transmissive intervals in the saturated zone. Because fracture minerals are products of past transport, these occur where

future transport is likely, and hence occur in particularly important locations for future interactions with radionuclide-bearing solutions.

Finally, the minerals of Yucca Mountain have been cataloged in relation to the extensive data from biological studies on health effects resulting from mineral dust inhalation. Minerals of various hazard rankings occur at Yucca Mountain, and their occurrences and abundances have been accurately determined. The occurrence of erionite, a known carcinogen has been emphasized, along with the geochemical environment necessary to form this mineral. To date, erionite has not been found in the repository horizon.

Activity 8.3.1.3.2.1.3 - Fracture mineralogy. The objective of this activity is to determine the distribution of minerals within fractures at Yucca Mountain, within all significant rock masses that might provide transport pathways with some component of fracture flow.

Previous studies were abstracted and revised for incorporation into the summary and synthesis report for this study (Bish et al., in prep.).

Forecast: Further studies involving microautoradiography, combined with fracture-flow studies and traditional batch sorption studies, will be used to obtain the information needed to determine the impact of trace minerals, such as smectite, for modeling the retardation of radionuclide transport. Staff will analyze and interpret the origin of calcite, opal, manganese-oxide, and clay minerals from the ESF on textural and geochemical bases. Samples from cores collected from drillholes near the ESF (especially USW SD-7, USW SD-9, and USW SD-12) will be analyzed to provide information on mineral variability with stratigraphic level. This information is needed to interpret the data from the ESF horizon. Mineralogy will be determined for approximately 175 borehole samples including specified intervals of USW NRG-7/7a, USW UZ-14, USW SD-7, USW SD-9, and USW SD-12 (with supporting data from USW H-3, USW H-5, USW WT-1, and/or UE-25 WT#17). The host rock and units along flowpaths beneath the host rock are particularly important in thermal stability modeling. Particular emphasis will be placed on the distributions of hydrous minerals and, in the repository horizon, the abundances and distributions of regulated hazardous minerals (e.g., crystalline silica).

3.2.3 Study 8.3.1.3.2.2 - History of Mineralogic and Geochemical Alteration of Yucca Mountain

The objectives of this study are to determine the timing, temperatures, and hydrologic conditions of past alteration at Yucca Mountain; and to study experimentally the dehydration of smectite, zeolites, and glass. Processes range from deep-seated past hydrothermal alteration to ongoing shallow mineral deposition along fractures and faults.

Project mineralogists completed Volume II of a summary and synthesis report (Bish et al., in prep.). Significant technical results from the report are summarized by report section under the respective activities of this study. For a summary of the significant results documented in the summary and synthesis report, see Section 3.2.2 of this progress report.

Activity 8.3.1.3.2.2.1 - History of mineralogic and geochemical alteration of Yucca Mountain. The objectives of this activity are to constrain the timing, geochemical transport, and paleohydrology of hydrothermal, diagenetic, and epigenetic alteration; to estimate the long-term thermochemical stabilities of important sorptive phases, such as clinoptilolite; and to investigate the evolution of phases such as silica polymorphs that can influence water composition, precipitation, and the stabilities of other silicate minerals.

The contents of Volume II of the summary and synthesis report (Bish et al., in prep.) are summarized here by report section.

Section 1.2. Syngenetic Alteration of Pyroclastic Rocks

This section of the report presents examples of syngenetic alteration in the tuffs of the Paintbrush Group that involved glass dissolution and transport of solutes through fractures. The dissolution of glass and precipitation of secondary minerals are described with respect to possible effects on rock hydrologic properties. Chlorine-36 studies in the ESF (Study 8.3.1.2.2.2 in Section 3.1.6 of this progress report) indicate that many of the pathways followed by percolating ground water with less than 50-year travel times to the Topopah Spring Tuff are syngenetic features such as cooling joints and breccia zones. Interpretations of the syngenetic features sampled for the chlorine-36 studies part of the water-movement test (Study 8.3.1.2.2.2) are based on research results from the alteration history study.

Section 1.3. Diagenetic Alteration

This section of the report presents the results of studies that investigated the timing and extent of diagenetic zeolitic alteration of the glassy non-welded tuffs. The timing of zeolitization has been investigated by petrofabric and potassium-argon studies. A conceptual model of diagenetic zeolitization explains the relationship of past tectonic events to the distribution of clinoptilolite-rich rocks. Chemical-textural studies of zeolitization examine the processes of glass dissolution and solute and colloid transport, revealing substantial mobility of "immobile" elements such as aluminum. The ionic or colloidal form in which aluminum traveled has not been established; the distribution of dissolved aluminum species is notoriously difficult to establish because of the many possible polymeric species, uncertainties regarding mineralogic controls, and complex sampling requirements.

Section 1.4. Regional Hydrothermal Alteration

The vertical distribution of illite and smectite minerals, established for three drillholes, permits a reconstruction of the paleogeothermal gradients across Yucca Mountain about 9 to 11 million years ago. This reconstruction, showing temperatures up to about 275°C in the northern part of Yucca Mountain, provides the basis for estimating the long-term thermal stability of sorptive minerals and the effects of elevated temperature on mineralogic reactions. This section of the report discusses the thermal stability of sorptive minerals at temperatures up to the maximum reconstructed paleotemperatures (275°C), so the estimates of long-term thermal stability include, but are not limited to, stability under all anticipated repository temperatures.

Section 1.5. Surficial Calcite-Silica Deposits

This section of the report describes the distribution, mineralogy, and geochemistry of surficial calcite-silica deposits exposed in trenches at Exile Hill, east of Yucca Mountain. The deposits have been shown to be of pedogenic origin. The presence of related deposits within the Bow Ridge fault demonstrates that at trench-size exposure scales surficial expressions of tectonic features, such as fault zones, may act as conduits for the downward movement of solutes and particulates from the soil zone. This section also reviews paleoclimatic evidence suggesting that much of the calcite and silica accumulated in the soil zone during periods when the climate was cooler than at present.

Section 1.6. Brecciation of the Topopah Spring and Tiva Canyon Tuffs

This study of bedrock brecciation reveals a wide variety of textures and origins for exposed breccias in Exile Hill trenches (calcite-silica study site), at Busted Butte, and at Yucca Mountain. Some breccias are directly or indirectly related to tectonic events, while others formed by purely surficial processes such as erosion and downslope movement.

Section 1.7. The Role of Colloids in Alteration and Transport

This section of the report describes the role played by colloids in natural syngenetic and diagenetic alteration and reviews evidence pertaining to the dehydration and crystallization of colloidal silica. Water-rich gels collected in the Rainier Mesa tunnel complex (40 km northeast of Yucca Mountain) are compared with the dried and crystallized relics of colloidal accumulations preserved in Yucca Mountain rocks.

Section 1.8. Present and Future Rates of Alteration Processes

This section of the report examines evidence pertaining to ongoing natural alteration processes at Yucca Mountain. A key issue is the continuing existence of clinoptilolite, a sorptive mineral that enhances radionuclide retardation. Clinoptilolite is stabilized by the high aqueous silica activity in equilibrium with cristobalite in Yucca Mountain. The kinetics of the transformation of cristobalite to quartz are slow enough at ambient temperatures that clinoptilolite beyond the range of repository thermal effects should remain stable. The main variable affecting the scale of repository thermal effects will be the design thermal load. No natural hydrothermal activity is expected at Yucca Mountain. Ongoing zeolitization of volcanic glass in the unsaturated zone has not been documented, but the exchangeable cation composition of existing zeolites has changed during interaction with ground water. Secondary minerals, mainly calcite and opal, continue to be deposited in fractures and voids down to depths of several hundred meters.

Section 1.9. Implications of Natural Alteration for Repository-Induced Processes

This section of the report presents natural analog studies of Yucca Mountain (self-analog) and other sites. These studies relate to the thermal stability of clinoptilolite, a mineral with high

radionuclide sorptive properties under repository conditions; expected repository-induced alteration of vitrophyre glass; the potential contribution of colloidal silica to actinide retardation; inferences about the thermal stability of sorptive clinoptilolite from studies of the Yellowstone geothermal areas; and isotopic studies of uranium transport at Peña Blanca, Mexico. Products of repository-induced alteration are expected to be smectite, clinoptilolite $\pm$ other zeolites, and opal-CT $\pm$ other silica minerals. Under ambient conditions, clinoptilolite below the potential repository is not expected to recrystallize to analcime within 10^5 years; therefore, the sorptive capacity is expected to be available to retard radionuclides released from the repository. Vertical temperature profiles from Buscheck et al., (1994) predict elevated temperatures throughout the CHn. The study plan 8.3.1.3.2.3 potentially will address the kinetics of the transformation in a quantitative manner.

Section 1.10. Remaining Uncertainties and Information Needs

This section of the report identified several technical issues that would benefit from additional characterization. The purpose of the proposed studies is to strengthen the understanding of how natural alteration has affected the distribution of hydrologic properties within variable altered units at Yucca Mountain.

Results from three published papers are included in this section. The first paper (Levy et al., 1996) describes alteration history research in the first 1.1 km of the ESF. Secondary mineral occurrences in the Tiva Canyon Tuff include breccia cements of mordenite, a fibrous zeolite, and vapor-phase deposits of silica, alkali feldspar, apatite, hollandite, amphibole, and zircon. Calcite is also a common secondary mineral in faults and fractures. Project mineralogists studied water and gas contents in fluid inclusions in calcites from a fault in nonwelded tuff and a fracture in densely welded tuff. Results of these studies suggest mineral deposition occurs under transient locally saturated conditions or under both saturated and unsaturated conditions. The interpretation of deposition under locally saturated conditions may disagree somewhat with the findings of Paces et al. (1996) who conclude that deposition occurred under unsaturated conditions. Further work may be needed to reconcile these observations. The two alternatives are difficult to distinguish because the bulk fluid-inclusion extraction procedure mixes the contents from a large number of individual inclusions. Calcite in the nonwelded tuff may have incorporated air from the unsaturated tuff adjacent to the fault. A highly altered interval within pre-Pah Canyon Tuff bedded tuff just above the top of the Topopah Spring Tuff appears to be a rootless feature associated with cooling and de-gasing of pyroclastic deposits, overprinted by later zeolitic alteration. The observed quartz, cristobalite, opal-CT, and fluorite have been widely identified as products of syngenetic devitrification and vapor-phase alteration in and above the Topopah Spring Tuff. Smectite, also an abundant secondary mineral at the ESF site, has been observed elsewhere at this stratigraphic level. Zeolitic alteration of nonwelded tuffs above the Topopah Spring Tuff, as seen in the ESF, has also been noted in drill core and outcrop at northeastern Yucca Mountain. The hydrologic and geochemical conditions that favored zeolitization only in certain areas of this stratigraphic interval have yet to be determined.

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The second paper (WoldeGabriel and Levy, 1996) explores possible reasons why the preliminary potassium-argon dates for clinoptilolite, the most abundant and widespread zeolite at Yucca Mountain, show a consistent pattern of increasing apparent ages (from 2 to 13 Ma) with depth. Only the isotopic ages from the saturated zone are compatible with geologic evidence suggesting an age >10 Ma for most of the zeolites. Factors were investigated that may be responsible for the young apparent ages in the unsaturated zone. Cation exchange with recharge water and argon diffusion under unsaturated conditions (processes that may be characteristic of the unsaturated zone) were evaluated experimentally for their effects on potassium-argon systematics. Cation exchanging a natural clinoptilolite with calcium-, cesium-, potassium-, and sodium-chloride solutions showed minimal effects on radiogenic argon content. However, clinoptilolite heated at 200°C for 16 hours in air lost a significant amount of its radiogenic argon compared with minimal losses from clinoptilolite heated in water at 100°C for over 5 months. Kinetic parameters associated with argon loss have not been estimated. Preliminary results indicate that argon loss from incompletely hydrated clinoptilolite may be a major factor contributing to the young apparent ages of clinoptilolite in the unsaturated zone at Yucca Mountain.

The third paper (WoldeGabriel et al., 1996) describes dating of coexisting authigenic minerals separated from altered tuffs in Miocene and Plio-Pleistocene lacustrine deposits in California. The purpose was to evaluate the usefulness of authigenic minerals for potassium/argon geochronology by dating minerals from sites spanning a wider range of ages than ones present at Yucca Mountain. The dateable authigenic minerals included clinoptilolite, erionite, phillipsite, K-feldspar, and illite/smectite. Eruption ages for some of the host tuffs were determined using the argon-40/argon-39 method on single sanidine and plagioclase phenocrysts. As stated above, these deposits are in California, are not part of the southwestern Nevada volcanic field, and were not included in the deposits dated by Sawyer et al. (1994). Isotopic ages of the authigenic K-feldspar and some of the zeolites are similar to the eruption ages of the tuffs and indicate early alteration. Apparent ages of authigenic minerals in structurally deformed parts of one of the deposits are much younger than the eruption age.

Activity 8.3.1.3.2.2.2 - Smectite, zeolite, manganese minerals, and glass dehydration and transformation. The objectives of this activity are to determine how minerals and glasses important in the rocks at Yucca Mountain will dehydrate and transform under expected thermal loads; and to investigate the ability of zeolites and smectites to rehydrate after the peak in temperature.

The sections of Volume II of the summary and synthesis report (Bish et al., in prep.) devoted to research results from this activity are summarized here by report section. For a summary of the significant results documented in the summary and synthesis report, see Section 3.2.2 of this progress report.

Section 2.2. Dehydration/Rehydration Studies of Zeolites

This section of the report contains information on experimental heating and dehydration of natural and cation-exchanged clinoptilolites. Contraction of the clinoptilolite lattice upon

dehydration may have irreversible effects on the hydrologic properties of zeolitic tuffs. Structural collapse of clinoptilolite caused by a modest temperature increase ($<100^{\circ}\text{C}$) will not reduce the radionuclide sorptive capacity.

Section 2.3. Dehydration/Rehydration Studies of Smectites

This section of the report presents preliminary results of smectite dehydration and rehydration studies that demonstrate significant hysteresis in the contraction and expansion of the crystal lattice.

Section 2.4. Dehydration/Rehydration Studies of Glasses

This section of this report describes the long-term and short-term dehydration and rehydration of Topopah Spring vitrophyre under ambient humidity and a variety of temperatures. Dehydration of vitrophyre from below the potential repository horizon has the potential to release a maximum of the equivalent of an 84-cm column of water, which is equal to 840 years of infiltration at 1 mm/yr. No mineralogic changes were detected in any of the samples heated for 3.4 years, even at 400°C .

Section 2.5. Remaining Uncertainties and Information Needs

Chemical data collected for the vitrophyre dehydration and rehydration experiments revealed a significant content of fluorine and chlorine in the glass. These data indicate that there may be potential for acid zones to form by leaching of these halogens, depending on the water-rock ratio and the dynamics of vapor and saturated systems, from the vitrophyre.

Although hysteresis in smectite hydration and dehydration is a well-known phenomenon, controversy exists as to whether hysteresis is a kinetic or an "equilibrium" effect. To investigate the origin of hysteresis, scientists examined sodium-exchanged smectite from Cheto, Arizona, using x-ray diffraction and thermogravimetry conducted under controlled humidity. Humidity was controlled using mass-flow controllers to mix dry and water-saturated nitrogen gas to produce the required humidity. Experiments for the hydration side of the hysteresis loop were set up first to equilibrate the smectite at 0 percent relative humidity for 7 hours, followed by equilibration at 12 percent relative humidity for 5 days while monitoring changes in weight and x-ray diffraction pattern. The smectite was then equilibrated at 90 percent relative humidity for 7 hours and brought back to 12 percent relative humidity to monitor the dehydration side of the hysteresis loop for an additional 5 days. X-ray diffraction results indicated that smectite came into structural equilibrium at 12 percent relative humidity by the first x-ray run at 2.5 hours on both sides of the hysteresis loop and did not change within instrumental precision over both 5-day periods. At 12 percent relative humidity on either side of the hysteresis loop, the sample consisted of a mixture of a zero water-layer smectite, a one water-layer smectite, and an interstratified zero-one water-layer smectite. The interstratified smectites corresponding to each side of the hysteresis loop appeared to be stable with time. The thermogravimetric analyses experiments corroborated the x-ray diffraction data. Sample weights equilibrated rapidly and are virtually constant with time. The results clearly show that the smectite structure and water

contents on each side of the hysteresis loop are stable (or metastable) and that hysteresis cannot be the result of a kinetic effect. The most likely explanation for the hysteresis is that it arises from a balance of expansive forces (e.g., hydration of the interlayer cation), which are functions of interlayer cation and relative humidity, with attractive forces (e.g., van der Waals and electrostatic forces), which are a function of the distance between the smectite layers.

Forecast: This study will correlate variations in alteration with existing data on hydrologic properties and identify needs for additional measurements. The work will require analysis of samples from the ESF and unanalyzed drillholes. Mineralogy-petrology expertise will be used to determine and evaluate the assumptions about mineral distribution and field-scale mineralogical features (e.g., vitric-zeolitic transition, syngenetic alteration zones) that are incorporated into transport models. The evaluations and documentation will incorporate ESF data on the abundance of transmissive features identified by mineralogical and textural studies to help define and support selection of input terms for recharge into the TSw. This effort will be closely integrated with the studies of hydrologic properties by performing mineralogic-petrologic analysis of hydrologic-properties samples. The study will also be integrated with isotopic studies of the water movement test.

3.2.4 Study 8.3.1.3.3.1 - Natural Analog of Hydrothermal Systems in Tuff

The objectives of the study are to improve the reliability of long-term predictions regarding hydrothermal rock alteration in devitrified welded ash-flow tuff; to test the capabilities of the EQ3/6 geochemical code through modeling of alteration mineral assemblages in natural systems; and to provide a better understanding of the origin of alteration mineral assemblages currently found in Yucca Mountain.

As part of an effort to consolidate work scopes, this study plan will not be written because much of the work overlaps activities in Study Plans 8.3.4.2.4.1 and 8.3.1.20.1.1 (discussed in Sections 5.2.2 and 3.14, respectively, of this progress report). Much of the work is a compilation effort to select analog site(s) combined with testing and/or calibration of the EQ3/6 code to reduce uncertainties in EQ3/6 applications.

No progress was made during the reporting period; this was an unfunded study. Work scheduled in support of this study has been suspended.

Forecast: No activity is forecast for this study.

3.2.5 Study 8.3.1.3.3.2 - Kinetics and Thermodynamics of Mineral Evolution

The objectives of this study are to investigate the kinetics of glass, zeolite, and silica polymorph transitions and their relationship to aqueous silica activity; and to provide thermodynamic data for clinoptilolite/heulandite, albite and analcime.

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Volume III of the summary and synthesis report (Bish et al., in prep.) describes the basis for evaluating expected repository-induced geochemical alteration primarily using experimental results, theoretical mineral stabilities, and computer models of potential repository behavior. The volume focuses on the stability and reaction kinetics of zeolites, clays, silica polymorphs, and volcanic glass. Thermodynamic data and stability relations among the zeolites, especially clinoptilolite, analcime, erionite, and mordenite, are extensively described and include models of expected reaction relationships. Hydration and dehydration reactions in clinoptilolite and clays are summarized as functions of potential repository conditions, and models of the impacts of these reactions on the hydrologic budget of pore water and zeolite water are discussed. For example, heating clinoptilolite in the nominal Yucca Mountain zeolite model to 150°C at 1 atm total pressure has the potential to release an amount of water equivalent to 3800 years of infiltration at 1 mm/yr infiltration rate. The effects of temperature and fluid composition in controlling the stability relations of minerals at Yucca Mountain are emphasized. Experimental data on the kinetics of dissolution and precipitation of clinoptilolite, cristobalite, and smectite/illite are described, and kinetic data for other minerals at Yucca Mountain are summarized. The content of the volume emphasizes the effects of silica polymorphs in controlling the kinetics of mineral evolution.

- Thermodynamic data for clinoptilolite, analcime, and mordenite were summarized from experimental data and literature values. A self-consistent method to evaluate the data was developed, and preferred thermodynamic values were identified.
- A theoretical model was developed that allows the calculation of thermodynamic properties to be calculated as functions of composition with estimates of errors. The model was used in evaluating mineral stability at Yucca Mountain, particularly with respect to the expected effects of elevated temperature.
- The thermodynamics of hydration and dehydration reactions in clinoptilolite, other zeolites, glass, and smectite were summarized from experimental data.
- A theoretical basis was developed for incorporating the effects of hydration and dehydration reactions involving clinoptilolite and other hydrous minerals. Model calculations of these effects were presented, including boundary condition calculations on the maximum likely effects based upon the expected temperature evolution.
- Kinetic data for the dissolution and precipitation of clinoptilolite, analcime, silica polymorphs, and the smectite/illite transformation were summarized from experimental data and literature values. The relative reactivities of these minerals were discussed, and silica polymorph dissolution/precipitation reactions were employed as rate-limiting steps in mineral evolution.
- Theoretical basis and applications were developed for evaluating the likely impact of kinetics on reaction modeling under the expected repository-induced geochemical alteration.

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- The stability relations among zeolites at Yucca Mountain were modeled using experimentally constrained thermodynamic data. Relative mineral stabilities were examined as a function of water chemistry, silica activity, and temperature. Stability relations among clinoptilolite-analcime; clinoptilolite/heulandite-erionite, and heulandite-stellerite were emphasized.

For a summary of the significant results documented in the summary and synthesis report, see Section 3.2.2 of this progress report.

A paper (Chipera and Bish, in prep.) describes the thermodynamic modeling of clinoptilolite-analcime equilibria that was completed to simulate the conditions under which clinoptilolite may transform to analcime at Yucca Mountain. Temperature, relative cation abundances, and silica activity are important factors in determining clinoptilolite-analcime equilibria. Increased sodium ion concentrations in either clinoptilolite or the fluid phase, increased clinoptilolite potassium ion concentration, increased temperature, and decreased aqueous silica activity all stabilize analcime relative to clinoptilolite, assuming present-day Yucca Mountain water compositions. However, increased calcium ion concentrations in either clinoptilolite or the fluid phase, increased aqueous potassium ion concentration, and increased aluminum to silicon ratios in clinoptilolite (i.e., heulandite) all stabilize clinoptilolite with respect to analcime. Assuming UE-25 J#13 water to be the chemical analog for Yucca Mountain water, the modeling indicates that clinoptilolite should remain stable with respect to analcime if temperatures in the clinoptilolite-bearing horizons do not significantly exceed 100°C. Even if temperatures rise significantly (e.g., to 150°C), not all clinoptilolite should alter to analcime. Perhaps more importantly, thermodynamic modeling shows that some Yucca Mountain clinoptilolites, particularly those rich in calcium and aluminum, have enhanced thermal stabilities compared to sodium- and silica-rich clinoptilolites.

Data on dehydration and rehydration behavior of several cation-exchanged clinoptilolites using water sorption isotherm measurements were analyzed to provide information on the thermodynamics of water in clinoptilolite. However, the thermodynamic analysis required an assumption regarding the maximum amount of water that clinoptilolite can accommodate ($\theta_{\max}$). Thermogravimetric analysis experiments at the highest relative humidities showed evidence of water condensation, hampering the ability to accurately determine $\theta_{\max}$. Thermogravimetric analysis results were augmented with structural data obtained using x-ray powder diffraction and Rietveld refinement methods. X-ray diffraction data were obtained from sodium- and calcium-exchanged clinoptilolite and two natural, unexchanged samples over a range of relative humidity from 0 to ~100 percent.

Rietveld refinements were conducted to determine the unit-cell parameters and water-site occupancies as functions of water-vapor pressure. The results of these experiments show that the unit-cell volume steadily increased with humidity. Unit-cell parameters for all samples at 100 percent relative humidity agreed within statistical uncertainty with those obtained for wet samples. Water-site occupancies changed systematically with changes in water vapor pressure, and 100 percent relative humidity values also agreed with data for wet samples. Therefore, these data confirm that extrapolations of thermogravimetric analysis data to 100 percent relative

humidity provide good estimates of $\theta_{\max}$. The thermodynamic data obtained for water in clinoptilolite appear to be accurate and can be used in modeling the effect of repository-induced heating of zeolitic rocks at Yucca Mountain.

A paper was completed on the origin of hysteresis in smectite hydration and dehydration (Chipera et al., 1996b) that described studies of a sodium-exchanged smectite from Cheto, Arizona using x-ray diffraction and thermogravimetry conducted under controlled humidity. Results clearly show that the different smectite structures and water contents on each side of the hysteresis loop are stable (or metastable) and that hysteresis cannot be the result of a kinetic effect. The most likely explanation for the hysteresis is that it arises from a balance of expansive forces (e.g., hydration of the interlayer cation), that are functions of interlayer cations and relative humidity, with attractive forces (e.g., van der Waals and electrostatic forces). The "attractive" forces are functions of the distance between the smectite layers. These results will be used in modeling the effects of repository-induced heating on smectite dehydration processes. (See also Activity 8.3.1.3.2.2.2 in Section 3.2.3 of this progress report.)

A study using a fully coupled calculation of cation-exchange and stability data for clinoptilolite and analcime has been completed. Previous studies indicate that the stability of clinoptilolite is governed primarily by temperature and aqueous silica and sodium activity. Adequate thermodynamic data now exist for clinoptilolite and analcime to provide a basis for a semi-quantitative analysis of the stability of clinoptilolite. In this study, primary calorimetric data were extended by a modified thermodynamic estimation procedure and were combined with data from recent cation-exchange (Pabalan and Bertetti, 1994) and hydration (Carey and Bish, 1996) studies to yield the thermodynamic properties of arbitrary compositions of clinoptilolite and analcime. The equilibrium breakdown of clinoptilolite to analcime was calculated assuming cation-exchange equilibrium with aqueous solutions with variable ratios of sodium to calcium and sodium to potassium, as functions of temperature and silica activity. The results show that the strong affinity of clinoptilolite for potassium or calcium over sodium limits the stability of analcime to silica-poor, sodium-rich solutions. The clinoptilolite stability field is maximized for aluminous compositions in equilibrium with siliceous analcime. Temperature decreases the stability field of clinoptilolite, but this effect is moderated slightly by the loss of water from clinoptilolite. Uncertainties in these results were estimated by comparing predicted and measured calorimetric data for clinoptilolite and analcime. The estimated uncertainties indicate that corresponding uncertainties exist in the size and extent of the predicted stability field of clinoptilolite.

A paper (Carey and Bish, 1996) was completed that presents a thermodynamic formulation for the sorption of H_2O by clinoptilolite. The formulation is based on data obtained from analyzing equilibrium data collected by thermogravimetry from 25 to 250°C and 0.2 to 35 millibars H_2O vapor pressure on near end-member calcium-, sodium-, and potassium-exchanged natural clinoptilolite samples. The molar Gibbs free energies of hydration for calcium, sodium, and potassium clinoptilolite are -36.13 ± 3.02 , -29.68 ± 3.77 , and -25.53 ± 1.37 kJ/mol H_2O , respectively. The molar enthalpy of hydration for these phases is -76.92 ± 2.88 , -74.19 ± 3.46 , and -67.78 ± 1.25 kJ/mol H_2O . Thermodynamic data in a highly simplified model for the heating of a pure clinoptilolite rock demonstrated that clinoptilolite

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dehydration reactions consume 70 to 90 percent more thermal energy than rocks that experience 6 percent of pore water only. The exact amount of cooling to be expected at Yucca Mountain can only be calculated in a fully coupled model such as FEHM.

Forecast: A conceptual model will integrate information for mineral evolution at Yucca Mountain using kinetic, thermodynamic, field, and analytical studies of mineral, glass, and water reactions. Data will be compiled from other studies and from the literature as appropriate. This activity will define and bound important mineral reactions in the host rock that may affect transport of radionuclides. This activity will support transport model development and calculations, as well as near-field studies. The conceptual model will be incorporated into a transport and thermohydrologic model such as FEHM, and sensitivity analysis of the effects of individual mineral reactions on radionuclide transport will be conducted.

Information obtained in these studies will be combined with information developed in the FY 1996 synthesis report for mineralogy/petrology studies (Bish et al., in prep.) to produce an updated conceptual model of mineral evolution. The effort will summarize the potential geochemical and mineralogical effects of thermal loading and the possible impacts on radionuclide containment and rock properties. This work will culminate in an overall model of the expected behavior of the secondary phases at Yucca Mountain as a function of time, temperature, water and mineral composition, and water-vapor pressure.

3.2.6 Study 8.3.1.3.3 - Conceptual Model of Mineral Evolution

The objectives of this study are to formulate a model to explain the observed distributions of minerals in Yucca Mountain. The evolution of framework silicates (feldspars, zeolites, and silica polymorphs) will be emphasized. The model will also address the general chemical evolution of vitric tuffs and will be used to predict future mineral evolution in the mountain caused by both natural processes and emplacement of a repository.

This study has been combined with Study 8.3.1.3.2; see Section 3.2.5 of this progress report.

3.2.7 Study 8.3.1.3.4.1 - Batch Sorption Studies

The objective of this study is to obtain sorption coefficients for key radionuclides as a function of important geochemical parameters. These studies will statistically evaluate the experimental results and will provide the data base that will be used to develop models to predict sorption coefficients under conditions not directly addressed by the experimental program.

A summary and synthesis report on radionuclide retardation studies (Triay et al., in prep.) describes activities in sorption (Activity 8.3.1.3.4.1.4) and sorption models (Study 8.3.1.3.4.3), solubility and speciation (Study 8.3.1.3.5.1), dynamic transport (Study 8.3.1.3.6.1), and diffusion (Study 8.3.1.3.6.2).

Activity 8.3.1.3.4.1.1 - Batch sorption measurements as a function of solid phase composition. The objective of this activity is to determine sorption coefficients for radionuclides on the zeolitic and vitric tuffs of the Calico Hills nonwelded hydrogeologic unit, on devitrified tuffs, and on pure minerals representative of the minerals present in the rock and fractures of the repository block.

A report (Triay et al., 1996a) was published that describes the main results of this activity. The study found that Np(V) sorbed well onto calcite and calcite-rich Yucca Mountain tuffs under oxidizing conditions in UE-25 J#13 and UE-25 p#1 well waters. This result indicates that neptunium will be significantly retarded under fracture-flow scenarios because of calcite coatings on the fractures. Neptunium sorption onto clinoptilolite-rich zeolitic tuffs in UE-25 J#13 well water (pH: 7–8.5) was moderate, increased with decreasing pH, and correlated with surface area and amount of clinoptilolite. Neptunium sorbed poorly onto zeolitic tuffs in UE-25 p#1 ground water (pH: 7–9) and onto devitrified and vitric tuffs in UE-25 J#13 and UE-25 p#1 waters (pH: 7–9). Iron oxides appeared to be passivated in tuffs, and did not seem to contribute to the observed neptunium sorption, even though neptunium sorption onto synthetic iron oxide is significant.

Activity 8.3.1.3.4.1.2 - Sorption as a function of sorbing element concentrations (isotherms). The objective of this activity is to characterize the dependence of sorption coefficients upon the aqueous concentration of the element being sorbed by developing isotherms for the radionuclide. This activity will develop isotherms for the radionuclides to be tested. These isotherm data will be incorporated into the sorption data base for use in determining element concentration levels at which precipitation begins to contribute to the measured sorption ratio, and in modeling sorption to predict retardation along flow paths.

A paper (Triay et al., 1996b) was completed that describes sorption of neptunium, uranium, and plutonium in Yucca Mountain tuffs using water from well UE-25 J#13. The main results are as follows:

1. Neptunium, uranium, and plutonium sorb appreciably to synthetic hematite in UE-25 J#13 well water.
2. Np(V) and U(VI) do not sorb appreciably to devitrified or vitric Yucca Mountain tuffs, albite, or quartz.
3. The sorption of neptunium onto clinoptilolite-rich Yucca Mountain tuffs and pure clinoptilolite can be fitted with a sorption distribution coefficient in the concentration range from 1×10^{-7} to 3×10^{-5} M.
4. The sorption of uranium onto these materials is not linear but can be fitted with nonlinear Langmuir or Freundlich isotherms.
5. The sorption of neptunium and uranium onto clinoptilolite increases with decreasing pH in the range from 7 to 8.5.

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6. The sorption of Pu(V) onto tuffs and pure mineral separates at pH 7 is significant (values of K_d are in the range of 4 to 400). Plutonium sorption decreases as a function of tuff type from zeolitic to vitric to devitrified and as a function of mineralogy from hematite to clinoptilolite to albite to quartz.

Activity 8.3.1.3.4.1.3 - Sorption as a function of ground-water composition. The objective of this activity is to measure sorption coefficients as a function of ground-water compositions anticipated along potential travel paths. These data will contribute to the sorption data base and support the sorption model development and performance assessment calculations.

The summary and synthesis report for this study (Triay et al., in prep.) discusses sorption of plutonium, uranium, and neptunium as functions of ground-water composition and pH. The solution and sorption behavior of plutonium is the most complex of all the elements of interest. The ground-water compositional parameter most critical to this element in the Yucca Mountain flow system is the reduction-oxidation potential. The available sorption data base suggests plutonium should sorb strongly to Yucca Mountain tuffs under most of the expected conditions. However, because the reduction-oxidation potential was not controlled in experiments performed to date, additional controlled experiments should be conducted. The recommendation is to bias the reduction-oxidation potential to a high level in a series of sorption experiments using several rock types and a water composition representative of the unsaturated zone. If the sorption coefficients obtained in these experiments are consistent with earlier results, plutonium can be classified with the strong sorbers, and a minimum coefficient of 100 mL/g could be used in performance assessment calculations. On the other hand, if the sorption coefficients are decreased by the elevated reduction-oxidation potential imposed, additional experiments will be needed to better define the appropriate range of sorption coefficients to be used in the calculations.

Uranium sorption appears to be controlled by pH, alkalinity, and alkaline earth ion concentrations. Its affinity for Yucca Mountain rock samples is generally low with the highest coefficients observed in zeolitic tuffs. The main gap in the available data base is for sorption coefficients on zeolitic and devitrified samples in contact with water enriched in calcium and magnesium at pH = 6.5 to 8.0. Recommendations have been made to perform two sets of experiments, one using water with high calcium and magnesium but low alkalinity, and the other using water with high calcium, magnesium, and alkalinity (e.g., UE-25 p#1). Samples of both zeolitic and devitrified tuffs should be tested.

Neptunium appears to sorb primarily by surface complexation and surface precipitation mechanisms. The carbonate content of the rocks used in experiments with neptunium appears to have a large impact on sorption behavior. The presence of ferrous iron on surfaces in the tuffs may also be a factor. The recommendation has been made to oxidize the samples before use in sorption experiments to passify any ferrous iron that may be present on surfaces. If the oxidation does not affect the sorption coefficient for the rock, a very weak acid leach should be used to remove potential carbonate minerals. If this also has minimal effect, the presently available sorption coefficient data base could be used for performance assessment. If either of these

procedures results in lowering of the sorption affinity, additional steps will have to be taken to derive appropriate sorption coefficients.

Activity 8.3.1.3.4.1.4 - Sorption on particulates and colloids. The objective of this activity is to determine if sorption of important radionuclides occurs on particulates or colloids that may be present in ground waters along potential transport pathways. Batch techniques, modified to accommodate the much smaller sample sizes, will be used to measure sorption. If any sorption is measured, the use of sorption coefficients alone may not accurately predict the transport of sorbed radionuclides.

No progress was made during the reporting period; this was an out-year activity.

Activity 8.3.1.3.4.1.5 - Statistical analysis of sorption data. The objective of this activity is to produce statistical correlations and error estimates. Various statistical approaches will be used on the sorption data to determine those variables (e.g., mineralogy, ground-water composition, and atmosphere) that most profoundly affect the sorption coefficients; to predict sorption coefficients as a function of mineralogy and, perhaps, ground-water composition; to estimate errors associated with predicted sorption coefficients; and to identify gaps in the experimental data.

No progress was made during the reporting period; this was an out-year activity.

Forecast: This activity will integrate the radionuclide solubility, sorption, and transport synthesis reports submitted in FY 1996 in order to identify the most technically defensible models that should be used in performance assessment to describe these processes. Sorption data will be collected on plutonium batch experiments using the minimum number of experiments needed to produce defensible plutonium sorption values. The effects of organics on actinide sorption will be assessed, and available ground-water data will be evaluated to address potential deficiencies in the sorption data base. Sorption data for minerals and ground-water chemistries resulting from planned thermal loads will be collected. Three activities will be performed in FY 1997 for site characterization: (1) microautoradiography studies, (2) reversibility studies of radionuclide sorption (especially onto colloids), and (3) integration of the summary reports (submitted in FY 1996) dealing with radionuclide solubility, sorption, and transport to identify the optimal models to be used for performance assessment.

3.2.8 Study 8.3.1.3.4.2 - Biological Sorption and Transport

The objectives of this study are to determine what effects microorganisms have on the movement of radioactive wastes (i.e., effects on transport) and to determine if microbial activities play a role significant enough to be included in a performance calculation for Yucca Mountain. The objectives will be accomplished by combining the results of laboratory experiments investigating the different mechanisms of microbial effects on transport (chelation, sorption, and colloidal interactions) with microbial analysis of samples collected from the ESF that will

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determine the numbers, metabolic activity, identity, and diversity of the indigenous population in Yucca Mountain.

The results of the work completed to date (Hersman, in prep.; Hersman et al., in prep.) demonstrate that there is a small but metabolically active and diverse population of microorganisms in all samples analyzed (Haldeman et al., 1996; Ringelberg et al., 1996; Kieft et al., 1996). Although no anaerobes were cultured (Clarkston et al., 1996), phospholipid fatty acid analysis indicates the presence of sulfate reducers (Ringelberg et al., 1996). The sulfate reducers could facilitate microbially influenced corrosion of primary containers.

The carbon-13 to carbon-12 ratios (Yang et al., in press) of subsurface carbon dioxide suggest that microorganisms are the source of the elevated subsurface carbon dioxide concentrations found in Yucca Mountain. If microbial activity were greatly enhanced by repository construction, carbon dioxide concentrations could increase and affect the pH of unsaturated zone waters. This, in turn, may affect the stability of sorptive phases such as calcite. The magnitude of such an effect, however, is currently unconstrained. Interestingly, further phospholipid fatty acid analysis indicates the presence of methanotrophs, suggesting that the source of the microbial metabolic activity is methane (Ringelberg et al., 1996).

Using results of the field data just discussed, laboratory results have been scaled to provide better understanding of the potential of the various microbial interactions to affect transport (Hersman, 1996). For example, using the average number of microorganisms found in Yucca Mountain, the chelation of radionuclides by siderophores could be estimated. Rough estimates suggest that there is enough siderophore in the rock to chelate nearly 4000 times the plutonium solubility value predicted by solubility calculations for pH 7.0, and 25°C. Admittedly, there are several assumptions associated with this estimate, but there is still significant potential for increased transport caused by chelation. This information is discussed extensively in the summary and synthesis report for this study (Hersman, in prep.).

The results of the dissolution studies were presented at a conference meeting, (Hersman et al., 1996) and a paper is being prepared for a journal article (Hersman, et al., in press). The results of this work demonstrate that microorganisms are capable of dissolving metal oxides aerobically.

Forecast: Planned work will support development of process models for site-scale unsaturated zone transport and waste package degradation that will be used in the total system performance assessment for the viability assessment. The work also supports the process model for site-scale saturated zone transport, and parts of the waste containment and isolation strategy that concern limited corrosion and low humidity, and key actinide concentrations that may be reduced by depletion and dispersion.

3.2.9 Study 8.3.1.3.4.3 - Development of Sorption Models

The objectives of this study are to model the sorption experiments on rocks and minerals representing the proposed repository block and to derive a capability to predict sorption coefficients for key radionuclides under water-rock conditions not included within the experimental program.

The study plan for this activity is combined with Study 8.3.1.3.4.1 (Batch Sorption Studies). (See Section 3.2.7 of this progress report.) The major findings of this activity have been reported in the Radionuclide Retardation Summary and Synthesis Report (Triay et al., in prep.) and are summarized here.

As early as 1982 (Daniels et al., 1982), it was shown that the K_d for cesium adsorption onto Yucca Mountain tuff could be predicted to within a factor of three using literature data for cation exchange. These predictions only considered competition with sodium. This simplification was made because there were no data for the cation exchange of the other alkali metals and alkaline earths present in UE-25 J#13 water.

The relative contribution of cation exchange to the adsorption of neptunyl onto zeolitic tuff sample G4-1506 from sodium bicarbonate solution was determined. The surface complexation of neptunyl has been shown to be inner sphere and noncharging (Triay et al., in prep.). Therefore, the surface complexation of neptunium is expected to be largely independent of sodium ion concentration. The results show a linear decrease in K_d with sodium concentration at the low sodium concentrations that are consistent with cation exchange. At high sodium concentration, the K_d asymptotically approaches 2.5 mL/g, consistent with surface complexation. The ion exchange component is larger than the surface complexation corresponding to a K_d of about 10 in 0.0022 M sodium bicarbonate. The relatively low K_d for neptunyl in a zeolitic tuff is likely the result of the large ion size and high hydration number. The K_d in pure sodium bicarbonate is larger than that observed in UE-25 J#13 water; this is the result of competition with the additional cations, calcium, magnesium, and potassium.

Surface complexation reactions with Yucca Mountain tuff have just begun to be studied (Triay et al., in prep.). The pH dependence of actinide adsorption can be readily explained with a combined surface complexation and ion exchange model. The effect of changing ground-water composition on neptunium adsorption has also been successfully modeled using a surface complexation model. The modeling of actinide sorption shows that high carbonate concentrations will severely reduce the ability to form surface complexes on tuff. The ion exchange of actinides appears to dominate surface complexation under normal conditions. Furthermore, divalent cations were found to be strong competitors for cation exchange sites found in Yucca Mountain tuff.

Organic carbon has been found in water samples from limestones and tuffs in Nevada (Choppin, 1992). The effect of natural organic materials on neptunium and plutonium sorption by iron and aluminum oxides and crushed tuff material were studied using model organic

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materials as surrogates and has been described in the Radionuclide Retardation Summary and Synthesis Report (Triay et al., in prep.) and is summarized here:

- The sorption of model organic material dihydroxyphenyl alanine on oxide surfaces follows the order aluminum oxide > iron oxide. For a given sorbent, the higher the pH, the more dihydroxyphenyl alanine is sorbed. Surface complexation is the most likely sorption mechanism.
- The sorption of plutonium on iron oxides generally follows the order hematite > ferrihydrite > goethite. The sorption of neptunium on iron oxide is higher than that on aluminum oxide. The sorption of neptunium on crushed tuff material was much lower than that on oxide surfaces.
- The sorption of plutonium and neptunium on iron oxides increases as the solution pH increases. The sorption of plutonium is much higher than that of neptunium on hematite, goethite, and ferrihydrite.
- The amount of neptunium sorption was not affected by any organic materials that were studied. The presence of the model organic materials, alanine, catechol, dihydroxyphenyl alanine and nordic aquatic fulvic acid did not influence the sorption of neptunium on tuff or on iron and aluminum oxides. This lack of an observable effect is presumably a result of the weak complexation between neptunium and the model organics.
- The sorption of plutonium on goethite and ferrihydrite was influenced by the presence of dihydroxyphenyl alanine. Increasing the amount of dihydroxyphenyl alanine resulted in higher sorption of plutonium on goethite and ferrihydrite. Alanine decreases the sorption of plutonium. In the system containing catechol, however, plutonium sorption was increased. The enhancement of plutonium sorption in the presence of catechol is probably caused by the reduction of Pu(V) to Pu(IV) by the organic. The inhibition of plutonium sorption in the presence of alanine may be caused by decreasing the free plutonium ion activity in solution by forming an alanine-plutonium complex. No effect of organics on plutonium sorption was observed in the hematite system, probably because of the relatively high sorptivity of plutonium on the hematite surface.

Forecast: This study will summarize the mechanistic models for sorption of radionuclides onto Yucca Mountain minerals. A summary report (describing the findings to date from Studies 8.3.1.3.4.1 and 8.3.1.3.4.3) is in preparation. The emphasis of the summary report for Study 8.3.1.3.4.3 will be on (a) summarizing available surface complexation models to describe radionuclide sorption, (b) evaluating the predictive capability of surface complexation models to describe radionuclide sorption onto pure minerals and whole rock, (c) assessing the value of spectroscopic studies for direct measurement of sorbed species and surfaces, and (d) describing the effects of organics on radionuclide sorption.

3.2.10 Study 8.3.1.3.5.1 - Dissolved Species Concentration Limits

The objective of this study is to determine the solubilities and speciation of important waste elements under conditions characteristic of the repository and along flow paths from the repository into the accessible environment.

Activity 8.3.1.3.5.1.1 - Solubility measurements. The objective of this activity is to specify the conditions under which solubility experiments will be conducted and then measure solubility limits of important waste elements under these conditions.

Project geochemists reviewed data concerning the solubility limits of the transuranic actinides (thorium, uranium, neptunium, plutonium, and americium) in the waters of Yucca Mountain. The generally low solubility of actinides implies that solubility may represent one barrier in the multibarrier approach to limiting potential radionuclide release and hence could enhance system performance. To assess the adequacy of the existing thermodynamic data bases for predicting the solubility of these radionuclides, data have been collected from relevant literature sources, and these data have been evaluated using the specific ion interaction theory formalism and analogies to other actinides of the same oxidation state. A paper (Tait et al., in prep.) describes the use of the specific ion interaction formalism to correct for ionic strength differences between experiments and to evaluate the consistency of data. The latter technique takes advantage of the large data base for uranium complexes that has been critically reviewed by the Nuclear Energy Agency. No experimental work or data collection was performed in this period.

Activity 8.3.1.3.5.1.2 - Speciation Measurements. The objective of this activity is to identify important aqueous species of waste elements under conditions described in Activity 8.3.1.3.5.1.1 and to determine their formation constants. Such thermodynamic information is essential to model the solubility of key radionuclides as described in Activity 8.3.1.3.5.1.3.

This activity has been deferred because of a lack of funding.

Activity 8.3.1.3.5.1.3 - Solubility modeling. The objective of this activity is to develop the thermodynamic models with a consistent data base needed to calculate waste element solubilities over the range of conditions expected at the site.

This activity has been deferred because of a lack of funding.

Forecast: Work during the forecast period is intended to determine whether Np(IV) solids may form under natural conditions at Yucca Mountain. Forcing conditions, including high temperature and control of Eh, will be imposed and are intended to provide constraints on both the kinetics and thermodynamics to test whether natural conditions at Yucca Mountain might be expected to produce Np(IV). Completion of these experiments should identify the final constraints on neptunium solubility.

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3.2.11 Study 8.3.1.3.5.2 - Colloid Behavior

The objective of this study is to determine the stability of waste element colloids under expected site-specific conditions that might be encountered at the repository or along flow paths toward the accessible environment.

Activity 8.3.1.3.5.2.1 - Colloid formation characterization and stability. The objective of this activity is to determine formation and stability of waste element colloids.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.3.5.2.2 - Colloid modeling. The objective of this activity is to develop models and parameters to calculate natural colloid concentrations and stability and to describe the disposition of the waste element species as the colloids break up.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Further work on this study has been deferred because of funding constraints.

3.2.12 Study 8.3.1.3.6.1 - Dynamic Transport Column Experiments

The objective of this study is to measure the breakthrough or elution curve for tracers through tuff columns.

The Dynamic Transport Column Experiments study plan was submitted to DOE/YMSCO and approved on September 30, 1996.

Activity 8.3.1.3.6.1.1 - Crushed tuff column experiments. The objective of this activity is to measure the rate of movement through crushed tuff columns of radionuclides relative to tritiated water and other well-defined chemical species or colloids.

A paper (Triay et al., 1996c) was published that describes the comparison of neptunium sorption results from batch and column experiments. This study found that values of the sorption distribution coefficient, K_d , for neptunium obtained from crushed-rock column studies using two sodium bicarbonate waters (UE-25 J#13 well water and water prepared to simulate UE-25 p#1 well water) and using zeolitic, devitrified, and vitric Yucca Mountain tuffs agreed well with those obtained earlier from batch sorption experiments under static conditions. The values of K_d can be used to predict the arrival time for neptunium eluted through the columns. Even though the K_d model cannot be used to fit the shape of the neptunium elution curves, the K_d yields conservative values for neptunium release from the potential repository site (Triay et al., in prep.). Also, neptunium never eluted prior to tritiated water, implying that charge exclusion does not exclude neptunium from the tuff pores. The column experiments corroborated the trends observed in batch sorption experiments: neptunium sorption onto devitrified and vitric tuffs is

minimal and sorption onto zeolitic tuffs decreases as the amount of sodium and bicarbonate/carbonate in the water increases.

Activity 8.3.1.3.6.1.2 - Mass transfer kinetics. The objective of this activity is to determine the elution rate of radionuclides as a function of water velocity for crushed tuff columns (homogeneous system), solid rock columns (heterogeneous system), and for pure mineral samples.

The elution of plutonium through crushed tuff was studied as a function of water velocity and the results were summarized in the summary and synthesis report (Triay et al., in prep.). The elution of Pu(V) through zeolitic, devitrified, and vitric crushed tuff was measured in columns with water from well UE-25 J#13 and synthetic UE-25 p#1 water. The shape of the elution curves for plutonium indicates that use of K_d values to predict plutonium transport through Yucca Mountain tuffs will conservatively predict plutonium releases. Previous batch sorption results indicate that plutonium sorption onto tuffs is a slow process and probably results from a reduction oxidation reaction occurring at the tuff surfaces. [See Activity 8.3.1.3.6.1.1 in Progress Report #14 (DOE, 1996b).] To verify the batch sorption results (which suggest that plutonium sorption, even to the lowest sorbing tuff type (devitrified), could be significant), the migration of plutonium as a function of flow velocity was measured in devitrified tuff using UE-25 J#13 and UE-25 p#1 waters. The column results confirm the trends observed using batch sorption techniques; the elution curves observed for these columns are consistent with slow sorption kinetics.

Activity 8.3.1.3.6.1.3 - Unsaturated tuff columns. The objective of this activity is to measure the relative migration rate of radionuclides through partially unsaturated rock columns.

A paper (Conca and Triay, 1996) was published that describes the validity of using batch sorption data to describe selenium transport through unsaturated tuff. This study used unsaturated flow apparatus (UFA™) technology (centrifuge-induced flow) to directly measure selenite (SeO_3^-) coefficients and hydraulic conductivity under unsaturated conditions on two Yucca Mountain tuff samples in UE-25 J#13 well water. (The study is described in Activity 8.3.1.3.6.1.3 in Progress Report #14 (DOE, 1996b).) The retardation factor for the selenite species was found to be 2.5 in both vitric tuff at 62.6 percent saturation and zeolitic nonwelded tuff at 52.8 percent saturation, which translates into a sorption distribution coefficient, K_d , of 0.9 mL/g for the vitric tuff and 0.8 mL/g for the zeolitic tuff. The average K_d for batch sorption experiments, using the same zeolitic tuff and UE-25 J#13 solutions, was 0.1 ± 0.2 mL/g, which, given the small K_d values, shows general agreement between the batch and column measurements. The unsaturated hydraulic conductivities during the experiments were 2.5×10^{-8} cm/s for the vitric tuff and 1.2×10^{-8} for the zeolitic tuff.

Activity 8.3.1.3.6.1.4 - Fractured tuff column studies. The objectives of this activity are to measure the transport and diffusion of radionuclides through naturally fractured tuff; and to examine the movement of tracers through naturally fractured Yucca Mountain cores to test the transport models.

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The fractured tuff column studies were summarized in the summary and synthesis report for this study (Triay et al, in prep.). In this report, data are presented to assess the retardation of radionuclides (such as technetium-95, tritium, and neptunium-237) by minerals lining fractures in tuff.

Natural fractures in the Yucca Mountain tuff may act as fast pathways for the release of radionuclides to the environment. Calculations of radionuclide transport often include this fast-pathways assumption, which may be too simplistic and lead to unnecessarily conservative predictions of radionuclide releases to the environment.

To date, analysis of the data obtained indicates the following:

1. Diffusion from the fracture into the matrix can take place even at relatively fast flow rates (like the ones used in these laboratory experiments),
2. Neptunium can be significantly retarded, even under fracture-flow conditions. Neptunium retardation in fractures could be caused by both diffusion into the matrix and sorption onto the minerals lining the fracture walls,
3. Contrary to previous assumptions about the role of fractures in radionuclide retardation, preliminary results from this experiment indicate that fracture flow does not necessarily result in a fast pathway for actinide migration through fractures.

Activity 8.3.1.3.6.1.5 - Filtration. The objective of this activity is to quantify the filtration of colloids and particulates by the tuff as a function of particle or pore size using solid tuff cores and fractured cores.

A paper (Triay et al., 1996d) was published that describes colloid-facilitated transport at Yucca Mountain. This study found that the colloid concentration in UE-25 J#13 well water is about a million particles per milliliter (for particle sizes larger than 100 nm). At this low particle loading, the sorption of radionuclides to colloids would have to be extremely high before the colloids could carry a significant amount of radionuclides from the proposed repository site to the accessible environment. Also, aggregation experiments to evaluate the stability of silica (particle diameter: 85 nm) and clay colloids (particle diameter: 140 nm) found that when the concentration of electrolyte in a carbonate-rich synthetic ground water is increased, aggregation is irreversible and the rate of aggregation increases with increasing electrolyte strength. The stability ratio for particle aggregation was determined, and the aggregation of silica and kaolinite clay particles decreased dramatically for an electrolyte concentration below 300 mM (millimolar) and 200 mM, respectively.

Forecast: The results of transport experiments consisting of eluting radionuclides through saturated and unsaturated, crushed, fractured, and solid tuff columns will be summarized. This summary will assess the validity of using batch sorption distribution coefficients to describe the migration of radionuclides through fractured and solid tuff under various degrees of saturation.

This summary will also assess the results of eluting colloids through tuff columns and the implications of those results for performance assessment calculations of radionuclide transport.

3.2.13 Study 8.3.1.3.6.2 - Diffusion

The objectives of this study are to measure the diffusivity and kinetics of adsorption in a purely diffusive system (that is, no advection) from the uptake of radionuclides on intact tuff as a function of time; and to conduct scaling studies to determine the length to which the matrix diffusion model can be applied with confidence.

Activity 8.3.1.3.6.2.1 - Uptake of radionuclides on rock beakers in a saturated system. The objective of this activity is to measure the uptake of radionuclides by rock beakers as a function of time.

The diffusion studies using rock beakers are summarized in the Radionuclide Transport Summary and Synthesis Report (Triay et al., in prep.) and are highlighted here. The results indicate that the diffusion coefficient for nonsorbing radionuclides into saturated Yucca Mountain tuff is on the order of 1×10^{-6} cm²/s. Large anions, such as pertechnetate, are excluded from tuff pores and their diffusion coefficients are on the order of 1×10^{-7} cm²/s. Comparing the predictions for the uptake of sorbing radionuclides by the tuff with the data obtained indicates that conservative transport calculations will result from predicting diffusion using the batch sorption coefficient for the sorbing radionuclide and the diffusion coefficient obtained for tritiated water (Section V.1 of Triay et al., in prep.).

Activity 8.3.1.3.6.2.2 - Diffusion through a saturated tuff slab. The objective of this activity is to measure the diffusion of radionuclides in a purely diffusive system (no advection) by observing the migration of radionuclides through slabs of Topopah Spring Tuff and Calico Hills zeolitic tuff.

The results indicate that the diffusion of nonsorbing radionuclides into saturated tuff (illustrated by the diffusion of tritiated water) is slower in devitrified tuffs than in zeolitic tuffs. Large anions such as pertechnetate (which are excluded from the tuff pores by size and charge) diffuse slower through the tuff pores than tritium regardless of the types of ground water or tuff. Sorption dominates the migration of plutonium through tuff under diffusive conditions. The migration of Np(V) and U(VI) through tuff depends on tuff type and water chemistry. When the reported sorption of neptunium onto tuff is essentially zero (Triay et al., 1996a; Triay et al., 1996b) the diffusion of neptunium through the tuff is slower than the diffusion of tritium but comparable to the diffusion of a nonsorbing, large anion, such as pertechnetate.

Activity 8.3.1.3.6.2.3 - Diffusion in an unsaturated tuff block. The objectives of this activity are to determine the distribution of radioactivity in the unsaturated tuff matrix, using an unsaturated block of the Topopah Spring Tuff or the Calico Hills Formation, and to fit the uptake of radionuclides as a function of time to a diffusion model with reactions (sorption) to determine the diffusivities and rate constants.

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The techniques used to study diffusion in unsaturated tuff are summarized in the Radionuclide Retardation Synthesis and Summary Report (Triay et al., in prep.). A major conclusion was that use of the unsaturated flow apparatus (UFA™) is the most efficient and cost-effective way to determine radionuclide diffusion coefficients (as functions of saturation) in samples of Yucca Mountain tuffs (see Activity 8.3.1.3.6.1.3 in this progress report and in Progress Report #14, DOE, 1996b).

Forecast: A report, summarizing the results of the diffusion experiments and providing diffusion coefficients as a function of hydrologic unit, tuff moisture content, and temperature, will be prepared. The report will describe the use of diffusion data to develop diffusion coefficients for radionuclides migrating through fractures into the tuff matrix in the presence of fracture coatings.

3.2.14 Study 8.3.1.3.7.1 - Retardation Sensitivity Analysis

The objectives of this study are to develop a conceptual geochemical-geophysical description of Yucca Mountain based on the results, data, and information generated from the geochemistry, mineralogy-petrology, hydrology, and other pertinent Project tasks; and to determine which data are most important to make the cumulative, integrated transport calculations needed to meet the U.S. Nuclear Regulatory Commission (NRC) and U.S. Environmental Protection Agency regulations. Another important function of this study is to provide process models from which performance assessment abstractions and simplifications can be made.

The study is the focal synthesis activity for hydrology, mineralogy/petrology, sorption, dynamic transport, and solubility/speciation tasks by incorporating information from all these sources into abstracted site-scale transport models for both the unsaturated and saturated zones.

Activity 8.3.1.3.7.1.1 - Analysis of physical/chemical processes affecting transport. The objectives of this activity are to analyze processes that may affect transport, geochemical, physical, particulate, heat-load effects, and coupled phenomena; to support and develop those laboratory experiments needed to examine the physical and geochemical processes affecting radionuclide transport and other experimental activities under this program and the ESF tests; and to correlate and validate results obtained from laboratory, ESF, and field experimental results with transport calculations.

Project hydrologists developed a comprehensive flow-and-transport model of the unsaturated zone at Yucca Mountain (Robinson et al., in prep.[a]) that considers various infiltration rate scenarios including spatially and temporally varying infiltration. As part of the calibration exercise for the unsaturated zone flow-and-transport model, environmental isotopes measured in boreholes and in the ESF were considered in simulations. These simulations (of chlorine-36 to chloride ratios and carbon-14 in the unsaturated zone) indicate that infiltration rates between 1 and 5 mm/yr are more consistent with the field measurements than infiltration rates, on the order of 0.1 mm/yr. Total system performance assessments performed for Yucca

Mountain routinely conclude that infiltration rate is a critical parameter for determining waste package lifetime, radionuclide release rates, and radionuclide migration in the natural barrier system (CRWMS M&O, 1995a). Thus, the calibration effort directly impacts studies in all these topics by providing tighter bounds on the infiltration rate at the site.

Previous environmental isotope simulations (Wolfsberg et al., 1996), augmented by more recent studies (Robinson et al., in prep.[b]), provide reasonable explanations for observations of chlorine-36 levels from weapons testing (see Study 8.3.1.2.2.2, in Section 3.1.6 of this progress report). Namely, disturbance of the PTn (such as faulting, which leads to increased bulk fracture permeabilities) provides a local hydrologic environment conducive to rapid fracture flow of a small (less than 1 percent) fraction of the total percolation flux. The flow in the fractures associated with these disturbances is rapid enough to transport solutes from the ground surface to the ESF in less than 50 years.

Activity 8.3.1.3.7.1.2 - Geochemical/geophysical model of Yucca Mountain and integrated geochemical transport calculations. The objective of this activity is to perform calculations of radionuclide transport from the repository to the accessible environment using, as a basis, an integrated, conceptual geochemical-geophysical model of Yucca Mountain.

Radionuclide migration simulations were performed in a series of model analyses ranging in scale from the near-field environment, to the site-scale unsaturated zone (Robinson et al., in prep.[b]), to the saturated zone (Zyvoloski et al., in prep.). The impact of the near-field conditions was considered for various backfill materials and hydrologic conditions. The source term, under release conditions, limited by both solubility- and waste-form dissolution rate, was approximately represented as a constant release rate until the inventory is depleted. For neptunium-237 (considered a solubility-limited radionuclide), the predicted time for complete release to the far field ranged from 1 to 132 ky at 1 mm/y percolation flux, and was proportional to the percolation flux for values in the range of 1 to 4 mm/y. For technetium-99 (a dissolution-rate-limited radionuclide) times for complete mobilization ranging from 0.6 to 60 ky were computed. These abstracted model results will be used to develop site-scale process level models and total system performance assessment analyses.

The chlorine-36 and carbon-14 results from the near-field transport model and from the model calibration studies were used to calculate estimates of transportation for key radionuclides in the unsaturated zone. For base-case hydrologic conditions, the following ranking was obtained for the radionuclides studied (ranking from highest to lowest based on peak dose at the water table): neptunium-237, technetium-99, uranium, selenium-79, and plutonium-242. In general, the nature of the release from the near field had little impact on the site-scale simulations unless significant rapid transport through fractures in the CHn was assumed (see the following discussion). An exception is uranium, which exhibits nonlinear sorption (See Activity 8.3.1.3.4.1.2) on zeolitized rock. A more concentrated pulse of limited duration exhibits less retardation than a longer, more extended release of uranium.

The role of rapid transport through fractures was studied for neptunium-237 using dual-permeability models. The model indicates that the peak dose may result from rapid radionuclide

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transport through fractures. However, this does not mean that most of the radionuclides travel through fractures. A typical split in these simulations shows 10 percent of the source radionuclides travel rapidly in the fracture system while 90 percent travel much slower in the matrix material. These results must be interpreted considering that the distribution of the simulated flux between the fractures and matrix is entirely the result of the parameters used to characterize the system.

Comparison of transport simulations with and without potential repository heat show that perturbations to the flow system from potential repository thermohydrologic effects are of such short duration, compared with the transport times to the water table, that they have almost no effect on the breakthrough curves. However, this analysis did not consider the effects of mass redistribution or phase changes involving solids on the intrinsic properties of the rock. Thus, this process-level model, that assumed isothermal conditions, confirms the results of performance analyses of site-scale radionuclide transport, provided there are no irreversible changes to the hydrologic and geochemical systems caused by heat from the potential repository.

The transport of neptunium-237, one of the key radionuclides in the inventory, has been simulated using a comprehensive geochemical transport model. The laboratory-scale speciation and sorption data for neptunium-237 were replicated using the reactive transport module of FEHM. Specifically, the model correctly simulated the transition from sorbing neptunyl cation to non-sorbing carbonate complexes at higher pH values in typical Yucca Mountain fluids. Furthermore, the effect of carbonate concentration in the fluid (varied by performing experiments in both UE-25 J#13 and UE-25 p#1 water) on speciation is also correctly represented in the model. When speciation calculations are performed during simulations of transport through the unsaturated zone, the calculations directly incorporate the effects of geochemistry on transport of neptunium-237. Significant retardation of radionuclides occurred in the zeolitized CHn units as long as the unsaturated zone fluid had a carbonate concentration that resembled that of UE-25 J#13 fluid. Recent bicarbonate ion measurements for unsaturated zone pore fluids reported by Yang et al. (in press) confirm this observation. Therefore, retardation of neptunium-237 in the zeolitized CHn units has been corroborated by this reactive transport model, thereby reducing an uncertainty for one of the crucial radionuclides in the inventory.

A preliminary saturated zone transport model (Zyvoloski et al., in prep.) was developed. This model used the results for neptunium-237 from the unsaturated zone to compute the peak dose at assumed accessible environment locations ranging from 5 km to 25 km down-gradient from the potential repository. Potential impacts of dilution from ground-water flow and dispersion were illustrated. The role of sorption in reducing peak dose is more complex than that of dispersion. When no rapid transport through unsaturated zone fractures occurs, saturated zone sorption has little effect on reducing peak dose. However, when the peak dose at the water table is controlled by fracture transport, saturated zone sorption is shown to reduce the dose at the accessible environment.

Activity 8.3.1.3.7.1.3 - Transport models and related support. The objectives of this activity are to verify the computer codes and to validate the models used in this study and to

identify important contributors to the uncertainties in retardation calculations (sensitivity analyses).

Improvements to the reactive-transport model increased the efficiency of simulation of the transport of multiple, interacting species in the solid, aqueous, or gas phases (Viswanathan, 1996, Viswanathan et al., in prep.). Equilibrium and kinetic reactions were being recast as systems of equations that can be solved as algebraic equations at each node to improve computational efficiency. This code development effort allowed the simulation of the geochemical transport behavior of neptunium-237 (see previous discussion under Activity 8.3.1.3.7.1.2). Also, a newly developed particle tracking option (Robinson and Henderson, in prep.) for time-varying input signals made possible the accurate simulation of site-scale measurements of environmental isotopes (chlorine-36 and carbon-14).

Forecast: This study will test the importance of uncertainty in conceptual models and parameters for flow and transport in the unsaturated and saturated zones and support performance assessment. To create abstractions suitable for performance assessment, the following model studies will be completed: (a) testing simple sorption and solubility models against complex, reactive transport models, and (b) developing reactive transport models for neptunium, uranium, and technetium in the unsaturated zone, and, for technetium in the saturated zone to test whether simple solubility and speciation and sorption models can be used in model abstraction. The reactive transport models will include solubility and speciation, dissolution and precipitation, and reduction-oxidation reactions in the presence of repository waste heat and the introduction of manmade materials. An important aspect of this work will incorporate the latest information from the mineralogy and petrology conceptual model.

Process models for radionuclide transport will be updated by incorporating and summarizing progress through FY 1996 and the first half of FY 1997. Updating documentation will be included for transport codes, meshes, etc., and will include conceptual insights into the processes involved in the migration of radionuclides through the natural barrier. Processes that affect the transport of radionuclides at Yucca Mountain will be studied to support the development of simplifying assumptions made by performance assessment for transport models. Retardation processes will be identified and ranked, and data accuracy requirements will be specified. These specifications will be used to assess the adequacy of site characterization data gathering activities.

Information will be incorporated from hydrology, mineralogy/petrology, sorption, dynamic transport, and solubility/specification tasks into site-scale transport models for the unsaturated zone. Where the data are unavailable and/or insufficient to accurately set parameter values, sensitivity analyses will be performed to determine effects that variations in parameters and/or processes have on radionuclide transport from the potential repository. Numerical flow and transport models developed for performance assessment will be used, along with enhancements, including reactive chemistry, that have been developed in previous years in this task. Radionuclide migration will be simulated, along with uncertainties, to identify additional data needs in the sorption, dynamic transport, hydrology, and geologic framework tasks.

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Two deliverables will be completed. One will include a conceptual model of the transport of radionuclides in the unsaturated zone at Yucca Mountain, including two- and three-dimensional integrated transport calculations and sensitivity analyses. Both equivalent-continuum and dual-permeability calculations will be made, incorporating discrete structural features as available and appropriate. The models will incorporate and consider isotopic data that indicate processes and rates of fluid flow or residence times in the mountain. The models will provide updated three-dimensional transport simulations for radionuclides including neptunium, plutonium, and technetium under ambient and thermally perturbed scenarios for two future climates and accompanying infiltration fluxes. The model will also be coupled to appropriate near-field source term and thermal model(s). Reactive transport models for key radionuclides, such as neptunium and uranium, will be developed to better capture the solubility/speciation and sorption data available for these radionuclides. The saturated zone flow and transport model will be updated by developing a set of fluid flow simulations that are consistent with the measured water table levels and available geochemical and isotopic information. Radionuclide transport calculations will be performed using this calibrated site scale model.

The second report will summarize model development and implementation for the reactive transport capabilities of the FEHM computer code. New options will be summarized, including speciation, complexation, and sorption reactive transport capabilities. Updated user documentation will also be provided, along with a series of example problems.

3.2.15 Study 8.3.1.3.7.2 - Demonstration of Applicability of Laboratory Data to Repository Transport Calculations

The objective of this study is to outline the strategy that will be used to demonstrate the validity of the laboratory generated geochemical data and the transport calculations using that data.

Activity 8.3.1.3.7.2.1 - Intermediate-scale experiments. The objective of this activity is to conduct experiments at a scale larger than a laboratory but with sufficient control on material and boundary conditions to test how increased spatial scale affects water flow and radionuclide transport in unsaturated porous media.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.3.7.2.2 - Field-scale experiments to study radionuclide transport at Yucca Mountain. The objective of this activity is to evaluate the validity of laboratory-derived data and models for radionuclide transport at the Yucca Mountain site by conducting tests in the bedded tuffs of the Calico Hills unit underlying the Topopah Spring unit.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.3.7.2.3 - Natural analog studies of radionuclide transport. The objective of this activity is to use natural analog studies and data generated by natural analog studies to

support long-term calculations of radionuclide transport using laboratory data and radionuclide transport models.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.3.7.2.4 - Data on radionuclide transport from other U.S. Department of Energy sites (Anthropogenic Analogs). The objective of this activity is to evaluate the validity of laboratory-derived data and models for radionuclide transport at the Yucca Mountain site by obtaining data collected at other United States DOE sites on radionuclide distribution in geologic systems.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No activity is planned for this study during FY 1997.

3.2.16 Study 8.3.1.3.8.1 - Gaseous Radionuclide Transport Calculations and Measurements

The objectives of this study are to calculate the rates of transport of gaseous radionuclide species between the repository and the accessible environment considering the various driving forces and retardation mechanisms that may exist; and to experimentally verify potential existing models of gaseous radionuclide transport and retardation that are used to assess radionuclide release to the environment.

No study plan will be developed; the scope of this study is encompassed by Study 8.3.1.2.2.6 and Activity 8.3.1.3.7.1.3.

Forecast: Further work on this study has been deferred because of funding constraints.

3.2.17 Related International Geochemical Work

No progress occurred during the reporting period. As of November 8, 1995, the subsidiary agreements under which the cooperative work had been conducted were terminated and all international collaboration was discontinued.

The OCRWM had bilateral and technical cooperative agreements with Canada (Atomic Energy of Canada Limited [AECL]), Switzerland (Swiss National Cooperative for the Storage of Radioactive Waste [Nagra]), and Sweden (Swedish Nuclear Fuel and Waste Management Company [SKB]) and has participated in activities of international organizations such as the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the Commission of European Communities (CEC).

3.3 ROCK CHARACTERISTICS (SCP SECTION 8.3.1.4)

The changes to the Rock Characteristics Program since the SCP was issued are summarized in Appendix A, Section A.1.3.

3.3.1 Activity 8.3.1.4.1.1 - Development of an Integrated Drilling Program

The objectives of this activity are to (a) ensure representativeness of data acquired during surface-based site characterization activities and that data represent the range of phenomena and structural characteristics needed for performance assessment, and (b) integrate and prioritize surface-based activities to produce a schedule that best addresses representativeness and efficacy concerns, given resource constraints.

There will be no study plan developed for this activity.

A Daily Field Activity Report has been distributed throughout YMSCO and to NRC.

A new Yucca Mountain Site Characterization Project Administrative Procedure - YAP 2.11Q, Surface-Based Test Management, was issued in July 1996. The planning process used for surface-based activities was streamlined by combining planning documents into a single Field Work Package that was implemented in May 1996.

Field Work Packages were completed for the following activities:

- FY 1996 Master Plan for Trench & Test Pit Reclamation
- Excavation of Test Pit Near Trench GDF-T5
- Installation of SEAMIST liner and instrumentation in Borehole USW UZ-14 (see Activity 8.3.1.2.2.7.1, Section 3.1.11 of this progress report).

Forecast: Limited drilling and surface-based testing activities will be completed in FY 1997. Future drilling activities for FY 1997 and FY 1998 have been prioritized on the basis of the needs of the hydrology program. Distribution of planning documents for the following activities is expected during FY 1997:

- C-Hole Work Period 3 (Tracer Testing)
- Borehole Workover and Pump Testing at UE-25 WT#17
- Field Testing for Borehole Sealing
- Paleoclimate Boreholes
- FY 1997 Master Plan for Trench and Test Pit Reclamation.

3.3.2 Activity 8.3.1.4.1.2 - Integration of Geophysical Activities

The objective of this activity is to provide a mechanism for information exchange, an analysis of data and other technical information, and an overview of planned geophysical site characterization activities.

Efforts during the reporting period concentrated on processing and analyzing geophysical data collected during the last half of FY 1995 and on developing reports summarizing the work and results of analyses. Synthesis continued for both the surface-based geophysics data set and the information available from borehole geophysical logging. Results of geophysical studies were used to support development of the three-dimensional integrated site model, including the geologic framework and distribution of rock properties, to help understand the tectonic framework of the site, to address issues related to volcanism, and to support ESF and repository design.

Work with borehole geophysical data focused on (a) completing forensic evaluations to assess the data quality and integrate the results of various logging runs, (b) developing an analytical model that supports analysis of borehole geophysical logs collected over the past several years, and (c) developing and completing reports on forensic and log analyses, the model description, and the synthesis of borehole geophysical data. Borehole geophysical log forensic evaluations were completed for boreholes USW SD-9, USW SD-12, USW SD-7, USW WT-2, USW WT-10, UE-25 WT#12, USW G-2, UE-25 UZ#16, USW UZ-14 and the North Ramp Geologic boreholes. (See Activity 8.3.1.4.2.1.3 for additional information on borehole geophysical studies.)

A report on the development of the balanced water model was completed in June (CRWMS M&O, 1996g). The balanced water model report includes the results from recent geophysical studies over and near the proposed repository block. These studies synthesized and integrated the results into consistent models that fit a combination of different geophysical data sets. The goal was to derive geophysical models and interpretations rather than forcing the data to fit a preconceived geologic model. The next iteration will derive a "best fit" geological model that incorporates the geological and geophysical data. This model can then be used by performance assessment to aid prediction of the performance of the proposed repository.

In general, the geophysical results indicate that the proposed repository volume at Yucca Mountain is composed of a sequence of tuffs with physical properties that vary throughout the repository region on a scale not captured in the current geologic model. The geophysical model conflicts with the layered, relatively unfaulted, gently dipping model now being used to predict transport behavior. The results of an investigation of the spatial variability of fracture and matrix porosities indicate that welding, lithophysal character and content, porosity, and mineralogy are variable over scales of tens of meters. Presently, variations in porosity caused by fracturing cannot be discriminated from those caused by large scale changes in matrix properties. However, where there is good surface evidence for faulting, faulting and fracturing appear to be the main causes for the variability in the geophysical data. The results imply that within the repository

volume the subsurface is heterogeneous and complex at a relatively small scale (i.e., the subsurface physical properties vary as indicated in the cross sections of seismic reflectivity).

Forecast: No new borehole geophysical data collection or analysis is planned in FY 1997. The near-term focus will be on cataloging and storing all acquired log data for future use. Efforts will continue to integrate geophysical data with geological information and interpretations to develop an understanding of the geological framework that is consistent with the total data set.

3.3.3 Study 8.3.1.4.2.1 - Characterization of the Vertical and Lateral Distribution of Stratigraphic Units Within the Site Area

The objective of this study is to determine the vertical and lateral variability and emplacement history of stratigraphic units and lithostratigraphic subunits within the Yucca Mountain site area.

Activity 8.3.1.4.2.1.1 - Surface and subsurface stratigraphic studies of the host rock and surrounding units. The objective of this activity is to determine the spatial distribution, history, and characteristics of stratigraphic units within the Paintbrush Group, Calico Hills Formation, Crater Flat Group, and possibly older volcanic rocks within the site area.

One of the primary purposes of this activity is to understand the lateral variations in hydrogeologic properties of various units within the Tertiary volcanic sequence. Recent techniques applied in correlating lithologic features with hydrogeologic properties, coupled with newly calculated porosity and saturation logs, have provided a means for determining the vertical and lateral continuity of potentially significant hydrogeologic layers (some of which are locally less than 1 m thick) and for correlating units across a site where only selected boreholes have been cored. Linkages of lithologic features, hydrogeologic matrix properties, and geophysical logs help to constrain variations in matrix versus bulk rock porosity, pore-space geometry, fracture-induced porosity, and occurrence of water in pore space or as structurally bound water, all of which are features that influence the flow of moisture through the site.

Staff geologists contributed a section on stratigraphy (Buesch and Spengler, in prep.) to the report on the hydrogeology of the unsaturated zone of the north ramp ESF (Rousseau et al., in prep.). The hydrogeology report was prepared as part of Study 8.3.1.2.2.3 (see Section 3.1.7 of this progress report). Selected elements of the existing three-dimensional lithostratigraphic model of the central block (see Activity 8.3.1.4.2.2.1, Section 3.3.4 of this progress report) of Yucca Mountain (Buesch et al., 1996a) were applied in evaluating the spatial characteristics of the model hydrogeologic framework. The model data base contains 74 boreholes, most of which are shown in Figure 3-2, and there are 13 modeled lithostratigraphic units within the Tiva Canyon, Yucca Mountain, Pah Canyon, Topopah Spring, and Prow Pass Tuffs with 8 modeled block- and subblock-bounding faults. Contacts of the modeled lithostratigraphic units serve as contour horizons for the several structure contour maps that were constructed, and variations in thicknesses of the units can be derived by comparing the elevations shown for the different contoured horizons. Fault orientations and displacements are also evident on the structure

contour maps. In addition to the lithostratigraphic contacts being modeled, several contacts were selected to coincide with (a) contacts of hydrogeologic units defined to support hydrologic studies, and (b) contacts of thermal/mechanical units defined to support engineering design of the ESF and of the potential repository. Three cross sections showing lateral changes in thickness and orientation of the lithostratigraphic units were extracted from the existing three-dimensional geologic model of the central block of Yucca Mountain (Day et al., 1996; see also Activity 8.3.1.4.2.2.1 in Section 3.3.4 of this progress report) to illustrate several geometric relations that are fundamental to interpretations regarding perched water and other features in the north ramp area. Detailed discussions of key lithostratigraphic and hydrologic units are included (CRWMS M&O, 1996f).

Activity 8.3.1.4.2.1.2 - Surface-based geophysical surveys. The objective of this activity is to improve confidence in stratigraphic models of Yucca Mountain by incorporating geophysical constraints.

A report by Ponce (in prep.) discusses geophysical data collected along 29 traverses across the central block of Yucca Mountain (see Activity 8.3.1.4.2.2.1, Section 3.3.4 of this progress report). Analysis of the data revealed anomalies associated with known faults and indicated a number of possible concealed faults beneath the east flank of Yucca Mountain. Two interpretative geophysical fault maps, based on data from gravity, ground magnetic, and aeromagnetic surveys combined with geologic mapping, depict possible fault locations or changes in the physical properties of the Tertiary volcanic bedrock. Major block-bounding faults such as the Bow Ridge and Paintbrush Canyon faults (Figure 3-3) can be traced from one profile to another. In general, however, locations of possible faults cannot be traced because of the severe terrain magnetic effects along the east flank of Yucca Mountain. The magnetic and gravity data reveal that (a) Midway Valley is characterized by several known and previously unknown faults, (b) the existence of the Yucca Wash fault is equivocal, (see also Activity 8.3.1.4.2.2.1), and (c) the central part of the eastern flank of Yucca Mountain is characterized by numerous low-amplitude anomalies that may reflect small-scale faults.

Interpretation of data from the intermediate seismic lines obtained across Crater Flat and Yucca Mountain suggest that moderate- to high-angle faults may extend to depths of 12 to 15 km with only modest changes in dip. Near Yucca Mountain, the base of the seismogenic layer at 12 km nearly coincides with the top of the reflective (ductile) lower crust at 15 km depth. These preliminary interpretations of the seismic reflection data confirm earlier conclusions that the inferred Paleozoic-Tertiary contact beneath Crater Flat and Yucca Mountain is offset by normal faults and could not represent an active shallow detachment surface.

The interpretation of regional seismic reflection data suggests that the Crater Flat-Yucca Mountain structural domain (see Figure 3-1 for general location) is an asymmetric fault-bounded half-graben having a maximum depth of about 4 km and a width of about 25 km. On the basis of truncation of a distinctive reflective fabric within Proterozoic and Paleozoic sedimentary rocks, the east-dipping Bare Mountain range-front fault bounding the structural domain to the west can be traced in the reflection data to a depth of at least 7 km with a constant dip of 45° (Brocher et al., 1996).

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Four independent data sets—aeromagnetic map, seismic reflection survey, mapping of exposed Tertiary volcanic units, and evidence from Quaternary fault scarps—define a 45-km² area in southern Crater Flat that contains steeply east-dipping normal faults with down-to-the-east displacements (Hunter et al., in press). These features appear anomalous to the regional structural grain in and near Yucca Mountain, where west-dipping normal faults that offset east-dipping volcanic strata are more typical of the geologic structure of the area.

The interpretation of these data by USGS staff indicates that the offset of the Paleozoic-Cenozoic unconformity by the Ghost Dance fault is about 1500 m. However, the interpretation presented in the synthesis of geophysical studies (Majer et al., 1996; CRWMS M&O, 1996g) indicates little offset at depth on the Ghost Dance Fault. Three-dimensional gravity models (Activity 8.3.1.4.2.2.5) are interpreted to be consistent with much smaller displacements of the unconformity. The displacement of pre-Tertiary rocks by the Ghost Dance fault is therefore indeterminate at the present time, since geologic control, which would constrain the offset of the pre-Tertiary unconformity by the Solitario Canyon and Ghost Dance fault zones, is lacking. Displacement of the Ghost Dance fault at depth is identified as an unresolved issue.

Activity 8.3.1.4.2.1.3 - Borehole geophysical surveys. The objectives of this activity are to help define and refine the location and character of lithostratigraphic units and contacts between units and to determine the distribution of rock properties within lithostratigraphic units.

The report, Synthesis of Borehole and Surface Geophysical Studies at Yucca Mountain, Nevada and Vicinity, consists of three volumes. Volume I (Majer et al., 1996) presents the interpretive summaries of geophysical logs collected for site characterization. Volumes II and III (CRWMS M&O, 1996g) contain the synthesis of borehole geophysical studies and summarize the status of the borehole geophysics studies that support the Project.

The use of geophysical logs in the identification of lithostratigraphic units continued to be evaluated. Variations in log signatures that may correspond to lithologic differences are leading to more accurate determinations of formation and unit contacts in the subsurface. Comparisons of contacts and log signatures for borehole USW SD-7, for example, have indicated that several contacts within the Tiva Canyon Tuff and Topopah Spring Tuff correlate well (to within 0.5 m stratigraphic thickness or less) with the geophysical log signatures. As reported in Activity 8.3.1.4.2.1.1, calculated porosity and saturation logs are being used to identify zeolitized rocks, and these types of logs, combined with bulk density logs, have been found to respond to depositional changes in texture and composition. A table of possible lithostratigraphic contacts that can be identified as input to the three-dimensional geologic model (see Study 8.3.1.4.2.3, Section 3.3.5 of this progress report) was prepared.

In support of the hydrogeologic investigation of the unsaturated zone in the north ramp of the ESF (see Study 8.3.1.2.2.3, Section 3.1.7 of this progress report), borehole video logs for boreholes USW SD-9 and USW UZ-14, combined with lithologic logs and video and photographs of cores, were examined to determine the dip of the Calico Hills Formation. Dips of 5° (east to southeast) did not require faulting but dips of 7° to 10° would require faulting.

Thirty-three borehole contact observations indicated that dips in the Calico Hills Formation near the two boreholes studied are 6° , and thus, appreciable dip-slip separation is not likely.

Borehole video logs from USW SD-7, USW SD-9, USW SD-12, and UE-25 UZ#16 were examined to determine the lithostratigraphic position and lateral extent of high-angle fractures in the Topopah Spring Tuff. Results indicate that the high-angle fractures are restricted to the middle lithophysal zone, but are well-developed only where this zone is thick and the lithophysae-bearing subzone in the middle (of the zone) is poorly developed or absent. In the ESF, the contact between the upper lithophysal and middle nonlithophysal zones of the Topopah Spring Tuff in the small-diameter vertical borehole at the entrance to the Northern Ghost Dance Fault Alcove (Figure 3-4) was determined to be at Station 37 + 37 (3737 m). The contact location was within 1 m of the position predicted with the three-dimensional lithostratigraphic model. This determination was made by examining video of the borehole wall, core video, and core from the ESF main drift multipoint borehole extensometer #12 vertical borehole. This work was done to support the engineering design for the Northern Ghost Dance Fault Alcove (Figure 3-4).

Activity 8.3.1.4.2.1.4 - Petrophysical properties testing. The objective of this activity is to provide geophysical and rock property data to be used in the interpretation of surface-based and borehole geophysical surveys.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.4.2.1.5 - Magnetic properties and stratigraphic correlations. The objective of this activity is to provide magnetic property data to aid in the interpretation of volcanic stratigraphy and structure of rock units, to use paleomagnetic directions to provide orientations for drill core segments, and to assess the rotation of rock units in relation to the geologic structures of Yucca Mountain from paleomagnetic indications.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: The stratigraphic nomenclature for existing boreholes will be revised to be consistent with the Reference Information Base lithologic description data item. Stratigraphic information will also be provided for continued development of the three-dimensional geologic framework model. The significance (in terms of implications for expected performance of the potential repository) of conflicting interpretations of the amount of offset on the Ghost Dance fault at depth will be evaluated. In particular, the need for additional geologic control from deep drilling will be evaluated.

3.3.4 Study 8.3.1.4.2.2 - Characterization of the Structural Features Within the Site Area

The objective of this study is to determine the frequency, distribution, characteristics, and relative chronology of structural features within the Yucca Mountain site area.

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Activity 8.3.1.4.2.2.1 - Geologic mapping of zonal features in the Paintbrush Tuff. The objectives of this activity are to map zonal variations within exposed tuffs that will aid in the identification of structural displacement at a scale of 10 m or less; and to detect subtle changes in structural styles.

The 1:6000-scale bedrock geologic map, structure sections, and accompanying text that describes the rock units (primarily within the Timber Mountain and Paintbrush Groups) and faults mapped across the central block of Yucca Mountain have been completed (Day et al., 1996). The central block is described as a structural mass of Tertiary volcanic rocks bounded on the west by the Solitario Canyon fault, on the east by the Bow Ridge fault, to the north by the Drill Hole Wash fault, and to the south by a line through an east-west stretch of Abandoned Wash. The major faults and their attendant splays within this area can be generalized into three main groups based on their orientation: north-striking block-bounding faults (Figure 3-3), northwest-striking faults, and intrablock faults. The main phase of fault movement is bracketed by the 12.7-Ma Tiva Canyon Tuff and the 11.6-Ma Rainier Mesa Tuff (Potter et al., in press); and there was renewed activity in Quaternary time on several of the major faults (see Study 8.3.1.17.4.6, Section 3.13.14 of this progress report).

The Bow Ridge fault (Figure 3-3) on the east side of the block, is a down-to-the-west normal fault with approximately 100 m displacement. In the ESF north ramp (40 m beneath the surface), the fault is a zone approximately 2 m wide and dips west at 60°. The Solitario Canyon normal fault (Figure 3-3), on the west side of the block, displays variable offsets. Toward its northern end in Yucca Wash, there is down-to-the-east displacement of approximately 70 m. To the south along most of its trace, the fault is downthrown to the west with displacements of more than 500 m. Within Solitario Canyon proper, deformation associated with the Solitario Canyon fault is a zone as much as 500 m wide. There is evidence of growth faulting during deposition of the Topopah Spring and Tiva Canyon Tuffs.

Northwest-striking faults were mapped in Sever Wash, Pagany Wash, and Drill Hole Wash, all north of the proposed repository blocks (Figure 3-2). Detailed mapping indicates that the latest motion on the Sever and Pagany Wash faults was right-lateral strike-slip. The Drill Hole Wash fault also demonstrates this same sense of movement, but locally displays a dip-slip component. In one exposure, for example, there is evidence of cumulative down-to-the-southwest displacement of approximately 15 m. In the ESF, two en echelon northwest-striking faults that are correlated with the Drill Hole Wash fault are downthrown to the west, but the dip-slip displacements are small. An inferred northwest-striking strike-slip fault, the Yucca Wash fault, was drawn beneath the surficial deposits of Yucca Wash by Scott and Bonk (1984), but the more recent and highly detailed mapping did not confirm that faulting occurred along this drainage course.

Numerous intrablock faults were mapped in the central block of Yucca Mountain, with the Ghost Dance normal fault being the main throughgoing structure (Figure 3-3). In general, the Ghost Dance is a north-striking fault zone, steeply west-dipping (75 to 85°) with down-to-the-west displacement. To the north, the fault is a relatively narrow zone (2 to 4 m wide) with as much as 6 m of dip-slip offset in Tertiary volcanic rocks. In its central segment, the fault zone

widens to 100 to 150 m and is made up of several splays with cumulative down-to-the-west offsets increasing to 15 to 20 m. To the south, the main zone bifurcates along strike and is also made up of numerous fault splays with generally less than 6 m displacement.

The Sundance fault was first identified by Spengler et al. (1994) and mapped as a series of near-vertical, N30°W- to N40°W-striking minor faults in a wide zone that extends across the northern part of the potential repository site. Recent mapping shows the zone to be about 750 m long and to have down-to-the-northeast displacement of 6 to 11 m. The Sundance fault cannot be traced across the Ghost Dance fault, nor is there any evidence that the Ghost Dance fault is offset anywhere along its northerly trend.

Between the Ghost Dance fault and the Bow Ridge fault to the east, numerous north-trending normal faults were mapped across the crests of eastward-extending ridges that form the east flank of Yucca Mountain; these faults were called the "imbricate fault zone" by Scott (1990). Displacements are commonly a few meters but locally are as much as 70 m, with both down-to-the-west and down-to-the-east displacements. Some of the faults closest to the Bow Ridge fault dip steeply eastward with down-to-the-east offsets, forming a series of grabens in the hanging wall block of the Bow Ridge fault. Another feature of hanging wall deformation is seen near the southeast corner of the central block, where an east-dipping reverse fault dips into the Bow Ridge fault, recording local compression. Reverse faults of limited extent also occur east of the Bow Ridge fault.

The relative timing of north-striking and northwest-striking faults is variable. Where exposed in the northern part of the central block, the northwest-striking faults are cut by the north-striking faults. This relation is best illustrated by the Pagany Wash fault, which terminates against the Solitario Canyon fault on its northwestern end and is cut to the southeast by a north-striking normal fault inferred to be associated with hanging wall deformation of the Bow Ridge fault. Elsewhere, however, a northwest-striking fault was observed to cut a north-striking fault within the "imbricate fault zone" of Scott (1990). This relationship has been interpreted to indicate that there is a second population of younger northwest-trending structures that are kinematically related to the north-striking faults. Still a third relationship between the two sets of structures was observed in places in the southeastern part of the central block where several of the north-striking faults merge into northwest-striking faults and en echelon pull-apart grabens, indicating that in this area the development of both fault types was coeval and therefore kinematically linked.

On the basis of the results of the detailed mapping just discussed, the structures of northern Yucca Mountain are interpreted to have formed in response to east-west to southeast-northwest extension accompanied by a northwest-directed dextral shear couplet. The dextral deformation is largely distributed as clockwise vertical-axis rotation of the blocks bounded by the north-striking faults. The clockwise rotation of the fault blocks is accompanied by left (oblique) slip on the north-striking normal faults. Thus, on a local scale, the structures in the central block appear to be best explained in terms of a sinistral shear couple regime that developed within a regional pattern of dextral shear. In summary, (a) the major set of northwest-striking faults are discrete expressions of dextral deformation along the northeastern boundary of the central block;

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(b) the left oblique-slip on the north-striking normal faults reflects a dynamic accommodation to clockwise (dextral) vertical-axis rotation of the blocks bounded by these faults; and (c) the secondary, younger population of northwest-trending structures formed within the major blocks in response to the left-oblique (sinistral) deformation occurring along the boundary faults. (See Activity 8.3.1.17.4.3.6, Section 3.13.11 of this progress report.)

Staff geologists working on this activity and the following activity (8.3.1.4.2.2.2) contributed a section on the structural setting of the north ramp at the ESF (Day et al., 1996a and in prep.[a]) to the report on the hydrology of the unsaturated zone of the north ramp of the ESF (Rousseau et al., in prep.) being prepared as part of Study 8.3.1.2.2.3 (Section 3.1.7 of this progress report). Descriptions of the dominant fault trends and fracture patterns along and adjacent to the ESF are given, particularly with regard to the Paintbrush nonwelded hydrogeologic and thermal-mechanical unit (PTn) within the Paintbrush Group (Figure 3-5), which is exposed locally in this area and was also encountered in the ESF. As observed in surface exposures, overall fracture intensity within the PTn unit is low, and the fractures are poorly connected within and between the several lithostratigraphic units represented. Each of these units appears to have its own fracture network with characteristic spacing, intensity, and termination style; however, most of the fractures are strata bound and terminate at welding breaks or lithologic breaks. Fracture intensity and connectivity increases with degree of welding within the welded units, but within nonwelded deposits fracture development is primarily controlled by lithology. In general, increasing pumice content is correlated to decreasing fracture intensity. In the ESF, the PTn exposures have much lower fracture densities than observed in outcrops. Nearly all discontinuities are minor faults with dips less than 75° and dip-slip displacements. The thickness and degree of welding indicate that the PTn unit would be more intensely fractured in the northern part of the area studied (north of Drill Hole Wash) than to the south, thus causing significant changes in structural and hydrologic properties from one locality to another.

Activity 8.3.1.4.2.2.2 - Surface-fracture network studies. The objective of this activity is to provide measurements and analyses of fracture networks to support modeling of hydrologic potential flowpaths, particularly in unsaturated zones. Applications are also expected to aid development of tectonic models and determination of the mechanical response of fractured rock to excavation and thermal loading.

A synthesis report discussing the results and interpretations of fracture studies conducted in the Yucca Mountain area over the past 15 years was completed (Sweetkind and Williams-Stroud, in prep.). The fracture data, primarily involving tuffs within the Miocene Paintbrush Group, are being used in (a) interpretations of the tectonic history of Yucca Mountain, (b) construction of simulated three-dimensional fracture network models, (c) development of surface infiltration models, and (d) determination of the effects of the fracture network on the stability of the rock mass during and after construction of the potential repository. Most of the volcanic units have very low matrix permeabilities; hence, the fractures and faults are the primary pathways for air and water flow into and out of the potential repository area. (See Activity 8.3.1.2.2.3.2 in Section 3.1.7 of this progress report.) The fracture network models thus provide

important and direct input to the modeling of flow in the unsaturated zone and to the modeling of pneumatic pathways.

Integration and analysis of the combined data collected from many thousands of fracture measurements (more than 10,000 from nonborehole sources alone) lead to the following general conclusions: (a) fracture intensity is dependent on lithology, variations in degree of welding, and proximity to faults; (b) connectivity of the fracture network also largely depends on lithology and degree of welding; and (c) width and intensity of fractured zones vary around faults and are related to the complexity of the fault. The degree of welding within units of the Paintbrush Group has the greatest effect on the overall character of the fracture network. Fracture intensity and network connectivity within the welded pyroclastic flows is much greater than in the nonwelded or poorly welded units, the differences being caused by higher numbers of both cooling and tectonic joints in the more brittle rock and by the presence of cooling joints that typically have longer trace lengths that enhance fracture connectivity. Connectivity within the Paintbrush Group as a whole is limited by the intervals of nonwelded, bedded tuffs that have largely strata bound fracture networks and very low fracture intensity, which are important factors in the hydrologic modeling of fluid flow within the potential repository. In general, the frequency and orientation of fracture sets within various units of the Paintbrush Group in the areas studied record the effects of regional stresses rather than the response to local conditions. As such, the general characteristics of fractures in unstudied areas and in the subsurface can be predicted. An exception to this generalization is that fracture intensities tend to increase near some faults and thereby represent zones of higher transmissivity than are found in less deformed areas. The overall effect of fractures in close proximity to fault zones, however, requires additional study.

Specific studies were undertaken to test the ability to predict subsurface structural features from surface observations (Sweetkind et al., in press). These studies indicate that numerous small faults (less than 1 m offset) identified within the ESF are generally not distinguishable at the surface because of lack of exposure or lack of suitable stratigraphic markers, or because minor displacements are accommodated within the fracture network before reaching the surface. Precision in correlating surface features with the subsurface decreases with depth for several reasons, including (a) some faults may have displaced units within the Topopah Spring Tuff, but became inactive before the younger Tiva Canyon Tuff was deposited; (b) many faults are discontinuous, both laterally and vertically, so that displacement may die out or step over to another structure between observation points; and (c) faults commonly splay upward, resulting in disparate surface and subsurface geometries.

Activity 8.3.1.4.2.2.3 - Borehole evaluation of faults and fractures. The objectives of this activity are to assess the reliability and usefulness of available borehole techniques for identifying and characterizing the subsurface fracture distribution; to determine vertical and lateral variability and characteristics of subsurface fractures; and to identify subsurface characteristics of fault zones.

Although this is an unfunded activity, work in conjunction with the surface-fracture network studies (see Activity 8.3.1.4.2.2.4) involved examining borehole cores and televiewer

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and sonic logs, as well as mapping fractures in the ESF, primarily to provide information on the variation of fracture frequency with lithology to support the modeling of hydrologic flowpaths.

Activity 8.3.1.4.2.2.4 - Geologic mapping of the Exploratory Studies Facility. The objectives of this activity are to determine the vertical and horizontal variability of fracture networks in the ESF ramps, drifts, and boreholes; to characterize major faults and fault zones in the subsurface; to map the lithostratigraphic features of the subunits and the abundance and character of lithophysal zones; and to assist in the evaluation of test locations in the ESF test facility.

At the end of this reporting period, the following mapping in the ESF had been completed: (a) full periphery field maps to Station 63 + 83 (6383 m); (b) detailed line surveys to Station 63 + 87.95 (6387.95 m), and (c) stereophotography to Station 62 + 71 (6271 m).

As indicated under Activities 8.3.1.4.2.2.1 and 8.3.1.4.2.2.2, results of fault and fracture studies of Yucca Mountain (Sweetkind and Williams-Stroud, in prep.) and in the ESF (Day et al., in prep.[a]) have been incorporated in a report on the hydrology of the unsaturated zone of the north ramp ESF (Rousseau et al., in prep.) prepared as part of Study 8.3.1.2.2.3 (see Section 3.1.7 of this progress report).

Activity 8.3.1.4.2.2.5 - Seismic tomography/vertical seismic profiling. The objectives of this activity are to investigate, and if successful, provide a means for broadly detecting and characterizing the subsurface fracture network in regions between the surface, boreholes, and underground workings; and to calibrate and relate the seismic propagation characteristics of the host rock to the fracture patterns observed in boreholes and underground workings, and extrapolate the observed fracture patterns to the surrounding region.

The amount, style, depth, and continuity of faulting in the proposed repository volume were studied using several geophysical methods. The most closely examined area was in the vicinity of the Ghost Dance fault. Vertical seismic profile, surface seismic, gravity, ground magnetic, and magnetotelluric methods were all applied in this region (Majer et al., 1996). The results of the regional geophysical surveys (Brocher et al., 1996) indicate that in this area the faulting is a classic example of steeply dipping Basin and Range extensional faulting with cross-cutting faults intersecting the normal faulting. There is abundant evidence of multiple sub-parallel fracture zones or faults associated with major mapped faults. This is most definitively shown for the Ghost Dance fault. Surface and borehole velocity studies across Yucca Mountain indicated that in addition to local heterogeneity, a general trend of increasing seismic velocity from north to south exists. This trend implies increasing porosity to the north.

The high resolution seismic work (Majer et al., 1996) in the repository region identified no seismic reflections from the interface between Paleozoic and Tertiary units. This is attributed to the combination of the small amount of energy penetrating to depth (high attenuation of the tuffs), and possibly a smaller contrast in the acoustic impedances between the Paleozoic rocks and the overlying tuffs.

Based on these investigations, the amount of offset of the Paleozoic-Cenozoic unconformity by the Ghost Dance fault is indeterminate, since geologic control is lacking (see Activity 8.3.1.4.2.1.2), and the energy sources for the shallow seismic work were not strong enough to unequivocally resolve such a deep feature. Three-dimensional gravity models are consistent with minimal offset of the unconformity beneath the repository block (comparable to surface offsets of a few meters), but data from regional seismic reflection studies (see Activity 8.3.1.4.2.1.2) were interpreted as a reflector corresponding to an offset of the unconformity of about 1500 m by the Ghost Dance fault (see Activity 8.3.1.4.2.1.2). If the unconformity is indeed affected by faulting of much greater magnitude than that expressed by offsets of the Paintbrush Group, then the majority of movement on the Ghost Dance fault would be constrained to have occurred prior to 12 Ma. Displacement of the Ghost Dance fault at depth is identified as an unresolved issue.

Forecast: The Site Area Geologic Map in support of the three-dimensional geologic framework model will be completed, and the geologic map of the central block of Yucca Mountain will be submitted for publication as a USGS Miscellaneous Investigations Map. Fracture studies will be conducted, in conjunction with other studies, to determine the structural controls, if any, on the occurrence of chlorine-36 in the ESF. Geophysical work in 1997 will focus on synthesis and modeling. This work will include the depth-to-magnetic-basement work and the final evaluation of the surface seismic data from both the repository and regional lines (Majer et al., 1996; Brocher et al., 1996, respectively). In terms of implications for expected performance of the potential repository, the significance of conflicting interpretations of the amount of offset on the Ghost Dance fault at depth will be evaluated. In particular, the need for additional control from deep drilling will be evaluated.

3.3.5 Study 8.3.1.4.2.3 - Three-Dimensional Geologic Model

The objective of this study is to develop a three-dimensional geologic model of the site area. In doing so, much of the study will involve the synthesis of the results of other studies in the investigation to develop a model that will be integrated into the three-dimensional rock characteristics model described in Study 8.3.1.4.3.2 (Section 3.3.7 of this progress report).

The three-dimensional Site Geologic Framework and Integrated Site Model of Yucca Mountain, version ISM1.0, was completed along with a report (CRWMS M&O, 1996i) describing the model. The rock properties inputs were based on compilations of data from lithostratigraphic logs from boreholes, geologic maps, measured sections, and results from geophysical studies. Lithostratigraphic horizons included in the framework model were determined from discussions with model users, including those modeling rock properties, radionuclide transport, and unsaturated zone hydrology. The framework model covers the site area from the topographic surface to the top of the Paleozoic section and includes more than 30 lithostratigraphic layers. Three-dimensional rock properties models and data were integrated into the geologic framework to form the integrated site model. Modeled properties include bulk and matrix porosity, density, hydraulic conductivity, and thermal conductivity. Version ISM1.0 was made available to all Project modelers.

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Subsequent to the delivery of version ISM1.0, work focused on compiling information to construct version ISM2.0. Besides data compiled for version ISM1.0, new geologic maps and geophysical interpretations were compiled and extensive workshops were held to integrate relevant data and interpretations from other studies. From these efforts, a first-pass three-dimensional model of faults was constructed and made available for comment. This model includes strike and dip information, as well as interpretations of relative ages and importances of faults. Faults to be included in version ISM2.0 were selected using the following criteria: (a) length greater than 3 km (2 miles) and offset greater than 30 m (100 ft); (b) significance to other studies; (c) significant effect on geologic map outcrop patterns; and (d) intersection with the ESF. The resulting set includes 61 faults. Work began to update the lithostratigraphic surfaces to incorporate new faulting information.

Forecast: The three-dimensional integrated site model (version ISM2.0) will be completed. After completion of version ISM2.0, work will begin to support model users and update the model. Work in 1997 will focus on synthesis and modeling of the geophysical data that has not been included in synthesis work to date. This new data includes depth to magnetic basement, and the results of the final evaluation of surface seismic data from both regional and local (repository-scale) surveys.

3.3.6 Study 8.3.1.4.3.1 - Systematic Acquisition of Site-Specific Subsurface Information

The objective of this study is to systematically acquire physical rock samples, analytical data, and basic descriptions of the subsurface geology of the repository site. These samples and information are important for characterizing the three-dimensional distribution of rock characteristics, and hydrologic and geochemical variables, for the unsaturated zone at Yucca Mountain. Only one activity is planned under this study.

Activity 8.3.1.4.3.1.1 - Systematic Drilling Program. The objective of the Systematic Drilling Program is to acquire rock samples, analytical data, and basic descriptions of the subsurface geology of the potential repository block for characterizing and evaluating the three-dimensional distribution of rock characteristics, and hydrological and geochemical variables. Core samples taken from selected drillholes provide information related to the design of the exploratory studies facility main test level and relevant geologic information required for understanding the deeper portions of the repository block.

No drilling or other field-based site characterization activities were conducted under this study. The geologic logs of drillhole USW SD-7 were completed, as were laboratory measurements of framework hydrologic properties.

Comprehensive reports describe the geology of the USW SD-7 drillhole (Rautman and Engstrom, 1996a) and of the USW SD-12 drillhole (Rautman and Engstrom, 1996b). These reports contain descriptions of geology; quantitative and semiquantitative information on fractures, lithophysae, core recovery, and rock-quality measurements; framework bulk and hydrologic properties; geophysical well logs; and x-ray diffraction mineralogical data.

The report for drillhole USW SD-9 (Engstrom and Rautman, 1996) has been revised to incorporate minor editorial and format changes. The content of this drillhole report is the same as that for the two reports (Rautman and Engstrom, 1996a and b).

Work products were provided to support several data synthesis reports and performance assessment analyses.

Forecast: Work in FY 1997 will focus on synthesis and modeling of drilling data that have not been included in synthesis work to date.

3.3.7 Study 8.3.1.4.3.2 - Three-Dimensional Rock Characteristics Models

The objective of this study is to produce numerical models of materials in space for use in various ESF design-evaluation and performance-assessment analyses, principally using geostatistical and other computer modeling methods. The study also will support the development of new computer algorithms and computer software required to accomplish the modeling.

Activity 8.3.1.4.3.2.1 - Development of three-dimensional models of rock characteristics at the repository site. The objective of this activity is to develop computer-based three-dimensional models that integrate quantitative and semiquantitative data on rock characteristics in light of constraining information developed by studies of the geologic framework of the Yucca Mountain site.

A report (Cromer and Rautman, 1996) was developed that describes the use of "soft" information from a three-dimensional geologic framework model in geostatistical modeling of material properties. Other reports (McKenna and Rautman, 1996; McKenna and Altman, 1996) describe the results of numerical scaling experiments and of a literature review of historical scaling algorithms.

The Yucca Mountain site-area geologic framework model, version YMP.ST5.0, was completely revised to incorporate previously unavailable data from regional geophysical surveys and interpretations, FY 1996 geologic mapping, and recently completed site characterization drillholes. Three-dimensional fault geometries were completely remodeled, and although the faults are still represented by vertical offsets, a number of inconsistencies and "impossible" geometric situations have now been resolved using data from additional geologic mapping. Computer files of the revised framework model have been incorporated into the Yucca Mountain Project Integrated Site Model, version 1.0 (CRWMS M&O, 1996i) (Study 8.3.1.4.2.3, Section 3.3.5 of the progress report).

Three-dimensional models of selected bulk properties, and hydrologic and thermal properties have been generated for two major stratigraphic units. Two different domains have been modeled: (1) the site-scale model comprises essentially the entire Yucca Mountain site area and has been discretized on a 250-m x 250-m horizontal grid spacing; and (2) a "repository west-

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block" model has been discretized on a 100-m x 100-m horizontal grid spacing. Both model volumes are discretized vertically on a nominal 10-m spacing.

Porosity data were compiled for all available drillholes (both "older" and post-1986 "site characterization" holes); porosity values comprised both laboratory core measurements and computed porosity values (Nelson, 1994) which have been derived from petrophysical well log data. Spatial continuity analyses were conducted using these data repositioned in stratigraphic coordinates (i.e., fault offsets and tectonic tilting were removed to represent the original depositional positions of the many data). Complete porosity models of the discretized volumes were then generated using sequential gaussian simulation techniques (Deutsch and Journel, 1989), and suites of 100 replicate simulations (one for each different volume and stratigraphic unit) were post-processed to produce three-dimensional arrays of the most likely (expected) porosity value at each grid node.

The individual porosity simulations (for each relevant suite) were used as surrogates (Flint et al., in press) to generate cross-correlated simulations of thermal conductivity and hydraulic conductivity using the geostatistical technique of linear coregionalization (Journel and Huijbregts, 1978). Bulk density "simulations" were generated from the porosity models by simple linear regression because the correlation coefficient between these two properties is effectively equal to one (Rautman et al., 1995).

Modeling hydraulic conductivity in the CHn required separate modeling of zeolitic alteration because the porosity-hydraulic conductivity relationships are very different in zeolitic and non-zeolitic tuffs. The available drillhole penetrations of the CHn unit were analyzed and each hole was converted to a vertical string of categorical indicators depending on whether the information at a given depth indicated that the rock was or was not zeolitic. A spatial continuity model for these indicator categories was developed (also in stratigraphic coordinates) and indicator simulations were produced to show the likelihood of zeolite prevailing at each of the discretized grid nodes. These simulations were post-processed to yield a three-dimensional representation of "expected" zeolite presence. This model of zeolitization was then used to combine suites of simulations representing "zeolitic hydraulic conductivity" and "nonzeolitic hydraulic conductivity." The resulting combined hydraulic conductivity realizations were also post-processed to produce a single model showing the most likely (expected) hydraulic conductivity within the Calico Hills-Prow Pass unit.

All expected-value rock property models were then restored to real-world coordinates by "hanging" the top of each stratigraphic unit from an appropriate structure-contour model extracted from the geologic framework model of CRWMS M&O (1996i). These final models were transferred to performance analysts working on coupled thermal-hydrologic modeling of the repository region, to modelers involved in the site-scale unsaturated zone hydrologic model (Study 8.3.1.2.2.9, Section 3.1.13 of this progress report), and to modelers developing the Site Geological Framework and Integrated Site Model, version ISM 1.0 (CRWMS M&O, 1996i) (Study 8.3.1.4.2.3, Section 3.3.5 of this progress report).

Forecast: Revisions to the geologic framework model will continue in anticipation of release of version ISM 2.0 of the Site Geological Framework and Integrated Site Model (Study 8.3.1.4.2.3). Changes in the fault model are expected as FY 1996 field mapping activities are completed. Additionally, the larger-offset faults will be converted to appropriately dipping breaks in the model wherever sufficient data for interpretation exist.

The three-dimensional rock properties models completed during FY 1996 will be revised and updated to incorporate additional core porosities, geophysical porosity values, and direct mineralogic indicators of zeolitic alteration. Correlations between the primary porosity variable and desired secondary properties will also be updated to reflect new information. Appropriate three-dimensional material property models will be generated for the PTn overlying the TSw section using effectively the same stratigraphic-coordinates/coregionalization technique. The rock properties models will be incorporated into version ISM 2.0 of the Site Geological Framework and Integrated Site Model (Study 8.3.1.4.2.3).

3.4 CLIMATE (SCP SECTION 8.3.1.5)

Changes to the Climate Program since the SCP was issued are summarized in Appendix A, Section A.1.4.

3.4.1 Study 8.3.1.5.1.1 - Characterization of Modern Regional Climate

The objective of this study is to provide a baseline for an analysis and interpretation of isotopic data from modern precipitation to provide an understanding of its seasonal and spatial variability.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No activity is planned for this study during FY 1997.

3.4.2 Study 8.3.1.5.1.2 - Paleoclimate Study: Lake, Playa, and Marsh Deposits

The objective of this study is to establish the nature, duration, and amplitude of paleoclimate changes in the Yucca Mountain area, based on paleontologic, geochemical, stratigraphic, sedimentologic, and geochronological data obtained from lacustrine, playa, and marsh sediments in or near southern Nevada.

Descriptions have been combined for all of the funded activities in this study, because they are closely related and because discussions of the results of investigations prepared by Project scientists for inclusion in a climate synthesis report (Forester et al., in prep.) apply to the study as a whole. Some of the study results were included in previous progress reports, and to some extent may be repeated here in the interest of presenting the status and overall progress of the

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lake, playa, and marsh deposit studies. The work for Study 8.3.1.5.1.2 was also closely coordinated with that of Study 8.3.1.5.1.3, Section 3.4.3 of this progress report).

A synthesis report discusses the results of all the investigations conducted within the site characterization climate program (Forester et al., in prep.). Data from studies of lakes, playas, and marshes show that the present southern Nevada climate exhibits an enormous precipitation deficit compared with earlier times during the Quaternary Period. Consequently, marshes and wetlands are rare in southern Nevada; the Pahrangat Marshes are the nearest wetlands to Yucca Mountain, and most surface water in the region is either runoff or spring discharge.

During the last and earlier glacial cycles, however, higher effective moisture supported higher water tables and increased runoff in most southern Nevada valleys. The paleowetland sediments contain a variety of fossils including mammals, molluscs, ostracodes, pollen, leaf impressions of trees and shrubs, and occasional diatoms. Deposits from the Las Vegas, Indian Springs, and Pahrump valleys, as well as Crater Flat, Lathrop Wells, and the Amargosa Valley along the Yucca Mountain flow gradient, were studied and fossils collected. The records from the Las Vegas and Indian Springs valleys provided climate and hydrologic information based on sediment stratigraphy and fossils. Data from a section at the Corn Creek Flat locality in Las Vegas Valley, in particular, provide environmental information that is representative of other studied sections in southern Nevada.

At the Corn Creek locality, fossil ostracode assemblages suggest an environment that was a permanent wetland featuring shallow, relatively fresh water. The wetland was supported by the regional water table and flowing springs during the penultimate glacial period (170 to 140 ka) and the early part of the middle Wisconsin (70 to 60 ka). The data suggest that mean annual precipitation at the Corn Creek locality during those times was about twice that of today (112 mm) with an unknown standard deviation. Ostracodes from one of the sediment units at Corn Creek commonly live in eastern Washington and western Minnesota at the present time, where the mean annual temperature is 5 to 7°C, and the effective moisture (mean annual precipitation minus mean annual evaporation) deficit is about one-fifth that in the modern day Las Vegas Valley. Radiocarbon ages document that the wetlands at the Corn Creek locality persisted until about 12 ka.

The growth and persistence of wetlands in southern Nevada are correlated to northern hemisphere summer insolation minima, associated with the last glacial cycle. Similarly, the eventual loss of wetlands is associated with a rise in the northern hemisphere insolation to its maximum value at 12 ka, and the retreat of the polar cell from the region. Such changes show that there is a linkage between millennial scale climate forcing functions and regional scale hydrology in southern Nevada.

Major assemblages of fresh water diatoms occur in sections of Owens Lake cored sediments dated as 470 to 430 ka, 400 to 330 ka, 260 to 220 ka, 170 to 120 ka, 70 to 60 ka, and 50 to 10 ka. In general, the fossils show these intervals featured cool, wet climates, and the intervening intervals (some of which are barren of fossils) featured shallow, alkaline water conditions. Thus, the diatoms define the long term climatic and hydrologic behavior of the

Owens River system. Overall, the stratigraphic continuity of freshwater diatoms in the Owens Lake sediments representing the past 500 ky indicates a longer and more persistent record of a fresh overflowing lake system (80 percent of the time) than of saline conditions such as those presently existing.

The ostracode record at Owens Lake shows a pattern of climate change similar to that of the diatoms, but in some respects the ostracode record indicates the interglacial and interglacial-glacial transition periods better than the glacial periods. Significantly, the microfossil data imply that the first two glacials in the past 400-ky climate cycle were not as wet or as cold as the last two recorded glacials. Applying that relation to the future would suggest that climate for the next 100 ky will not be as wet or as cold as that of the past 200 ky. Both the diatom and ostracode records at Owens Lake show a transition from interglacial to glacial conditions about 400 ka, which, given the cyclical (400 ky) nature of climate, suggest that present climate will soon shift toward a glacial period.

The walls of Devils Hole (Figure 3-1), are lined with calcite precipitated from water. Isotopic variations in the vein calcite and numerous radiometric age determinations, show that key features of global climate change related to changes in insolation are all recorded in southern Nevada (Szabo et al., 1994; Coplen et al., 1994; Winograd et al., 1988 and 1992). Although the timing of these climate changes are not synchronized with changes in insolation, the appearances and disappearances of the glacial/interglacial subcycles occur within a few thousand years of the times predicted by insolation parameters.

Activity 8.3.1.5.1.2.1 - Paleontologic analyses. The objective of this activity is to assemble and interpret, in paleoclimate terms, detailed fossil records from ostracodes, diatoms, and pollen, along with other types of fossils as warranted by specific paleoclimate questions.

See the discussion under the heading for Study 8.3.1.5.1.2.

Activity 8.3.1.5.1.2.2 - Analysis of the stratigraphy-sedimentology of marsh, lacustrine, and playa deposits. The objectives of this activity are to identify and characterize the general physical and chemical properties of sedimentary units from outcrops, shore deposits, and cores (providing a physical and relative temporal framework for various paleoenvironmental studies), and to determine the specific environment of deposition for the sedimentary units using the principles of clastic and chemical sedimentology.

See the discussion under the heading for Study 8.3.1.5.1.2.

Activity 8.3.1.5.1.2.3 - Geochemical analyses of lake, marsh, and playa deposits. The objective of this activity is to assemble and interpret, in paleoclimate terms, detailed records of stable isotopic, trace metal, and mineralogical data. The resulting interpretations provide the climate framework within which Yucca Mountain infiltration, percolation, recharge, and water-table elevation may be understood in climate terms.

No progress was made during the reporting period; this was an unfunded activity.

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Activity 8.3.1.5.1.2.4 - Chronologic analyses of lake, playa, and marsh deposits. The objective of this activity is to obtain an accurate chronologic framework for the paleoclimatic information acquired in this study. All age information should, whenever possible, be tested with other techniques to reduce uncertainties.

See the discussion under the heading for Study 8.3.1.5.1.2.

Forecast: Collection and compilation of microfossil and isotopic data from cores taken in Owens Lake will be completed. Additional microfossil and isotopic analyses will be conducted of core sections deemed critical for synthesis or necessary for ongoing related studies. Data collection will continue from critical sites along possible ground-water flow paths down gradient from Yucca Mountain to fully develop and understand aquatic environments along these flow paths based on interpretations of microfossils. Aquatic microfossil and isotope data sets will be integrated with those from the terrestrial paleoecology study (8.3.1.5.1.3) for compatibility and consistency.

3.4.3 Study 8.3.1.5.1.3 - Climatic Implications of Terrestrial Paleoecology

The objectives of this study are to provide quantitative estimates of changes in climatic variables (e.g., precipitation and temperature) for the southern Great Basin; develop transfer functions, response surfaces, or both by statistically comparing modern climate to the vegetation data; and reconstruct climates from the paleovegetation data using these equations.

Periods of wetter climate, their frequencies, magnitudes, rates of onset and decline, and shifts in seasonal distributions are being identified using data from plant remains from packrat (*Neotoma* sp.) middens. One hundred and ninety-five radiocarbon dates on plant macrofossils collected from 122 middens in southern Nevada provide proxy data to interpret past levels of mean annual precipitation and mean annual temperature. The studies focused on (a) direct and high-precision dating of key plant species and (b) multiple dates on several species from the same midden strata for age confirmation.

The interpretations of past climate based on terrestrial records (this study) and on aquatic records (Study 8.3.1.5.1.2) show a remarkable degree of convergence, supporting the conclusion that a much higher level of effective moisture existed during the Pleistocene than presently.

Activity 8.3.1.5.1.3.1 - Analysis of packrat middens. The objectives of this activity are to use radiocarbon dated macrofossils of climate indicator plant species to (1) identify periods of greatest late Quaternary precipitation, (2) determine durations of these periods, and (3) determine the rates of onset and demise of these periods.

Limber pine (*Pinus hexilis*) macrofossils appear in the packrat (*Neotoma* sp.) midden record of southern Nevada from ~11 to 13 ka, 14 to 21 ka, 23 to 26.5 ka and 30 to 33 ka. When viewed together with episodes of limber pine expansion, periods of white fir (*Abies concolor*) translocation are centered at ~12 to 13 ka, 14 to 16 ka, 21 to 26.5 ka and ~32 to 35 ka. The

wettest periods, based upon the exclusion of limber pine, occurred between 21 to 23 ka and 33 to 35 ka. These wet periods appear to coincide with the onset and demise of the last glacial maximum and an earlier cold/wet period. Onsets and demise of such periods appear to be rapid, on the order of ~100 years or less (Forester et al., in prep; Taylor et al., 1993; Mayeweski et al., 1993; Woillard, 1979).

Activity 8.3.1.5.1.3.2 - Analysis of pollen samples. The objectives of this activity are to use high frequency pollen records from southern Nevada to (1) determine the frequencies, rates and magnitudes of current Holocene climatic change, and (2) provide baseline data for the generation of analogs or transfer functions of high resolution climate change for the interpretation of less complete Pleistocene paleoclimatic proxy records.

Analysis of pollen samples removed from the cores from Lower Pahranaagat Lake at a resolution of approximately a sample every 13 to 14 years have been analyzed down to ~3.7 ka. Sampling has been completed down to approximately 5.6 ka. Comparisons of the results from ostracode samples from the first set of cores from Lower Pahranaagat Lake with the pollen record indicate that rapid shifts (about every decade) from periods of increased rainfall to severe drought and back again. Evidence for these shifts include the following: Pollen from plants that live under more moist conditions indicate that wetter conditions persisted in the past. Correspondingly, ostracodes in the lake reflect direct input into the lake of surface runoff. Conversely, drier terrestrial conditions, reflected by increases in saltbush and other desert shrub, correspond with ostracodes indicating a lake supported primarily by spring discharge. During the last 3.7 ka, periods of wetter climate have apparently occurred about once every 500 years (2.7, 2.0, 1.6, 1.2, and 0.3 ka) that appear to have high precipitation variability and major dry periods that appear to have low variability. Geomorphologists seeking evidence of a change in the damming mechanism of Lower Pahranaagat Lake have investigated a major shift in the aquatic record centered about 1.4 ka that does not have a corresponding shift in the terrestrial record. This change appears to have resulted from a major increase rainfall that disrupted the alluvial fan.

Activity 8.3.1.5.1.3.3 - Determination of vegetation-climate relationships. The objective of this activity is to translate the vegetational records provided by packrat midden and palynological investigations and available dendroclimatological data into qualitative estimates of past climatic variables.

Late Glacial episodes of white fir (*Abies concolor*) expansions suggest that Pacific air masses played a greater role in the climates of southern Nevada at that time than they do currently. The absence of white fir in communities with abundant limber pine (*Pinus hexilis*) indicates that periods of cold, dry continental climates (continental Polar and arctic air mass predominance) occurred from 16 to 21 ka and 29 to 32 ka.

Packrat (*Neotoma* sp.) middens indicate rapid shifts toward century to millennia-long wetter, winter precipitation patterns. This conclusion was drawn, using the modern mean annual precipitation requirements of key plant species and changes in plant species distribution during the Pleistocene as revealed in the plant macrofossil data from Nevada. Modern analog plant

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species mean annual precipitation ranges suggest a Pleistocene mean annual precipitation range of from at least 380 mm (17 in.) up to 635 mm (25 in.) at elevations between 1500 and 2000 m (4920 and 6562 ft). This is an increase of roughly 90 percent above the current range of between 200 to 250 mm (8 to 19 in.). During the Pleistocene Utah juniper (*Juniperus osteosperma*) occupied areas currently populated by xeric shrub species at elevations from 1500 to ~ 700 m (4920 to 2295 ft), precipitation was approximately 33 to 66 percent [a gain of 50 to 100 mm (2 to 4 in.)] above current values. Whereas current mean annual precipitation at these elevations is only 150 mm (6 in.) (Forester et al., in prep.), the Pleistocene mean annual precipitation was at least 200 mm (8 in.) or even up to about 380 mm (15 in.). However, most of the Pleistocene between 35 and 12 ka was dominated by more continental conditions characterized by cold-dry climate about 1.33 times wetter than today (Forester et al., in prep.).

These reconstructions indicate Pleistocene precipitation gradients were steeper. The Pleistocene difference in mean annual precipitation between ~ 750 m (2500 ft.) and ~ 1500 m (5000 ft.) reveals that precipitation was ~ 50 percent greater than should be expected at 1500 m (5000 ft.). This gradient indicates dramatically enhanced orographic precipitation effects between these elevations during the late Pleistocene. These data are summarized in Table 3-8 for elevations around 1500 m (5000 ft.). At elevations around 750 m (2500 ft) estimates should be about 50 percent of those at 1500 m (5000 ft). Above 2000 m (6550 ft) absence of data prevents estimation. Climate designations of Very Wet, Wet and Dry are relative.

Forecast: No activity is planned for FY 1997. Any additional activity is pending the identification of specific data needs and assignment of funding.

Table 3-8. Summary of Precipitation Between 35,000 and 12,000 Years Ago
for 1500 m Elevations

Period (ka)	Description (period)	Mean Annual Precipitation
~35-33	Very wet	~ 560-635 mm (22-25 in)
33-26.5	Dry	~ 405-460 mm (16-18 in)
26.5-23	Wet	~ 460-560 mm (18-22 in)
23-21	Very wet	~ 560-635 mm (22-25 in)
21-16	Dry	~ 405-460 mm (16-18 in)
16-14	Wet	~ 460-560 mm (18-22 in)
14-13	Dry	~ 405-460 mm (16-18 in)
13-12	Wet	~ 460-560 mm (18-22 in)

3.4.4 Study 8.3.1.5.1.4 - Analysis of the Paleoenvironmental History of the Yucca Mountain Region

The objectives of this study are to evaluate the paleoenvironmental record at Yucca Mountain and surroundings in light of inferred paleoclimate history of the southern Great Basin; to provide information to distinguish the effects of surficial processes from those of tectonic activity, based on the character and distribution of surficial deposits; and to evaluate the age of tectonic events.

Activity 8.3.1.5.1.4.1 - Modeling of soil properties in the Yucca Mountain region. The objectives of this activity are (a) to determine the relations among properties of late Holocene soils and climatic parameters; (b) to compare properties of selected soils at Pahute Mesa and near Tonopah that formed under conditions similar to those that may have existed at Yucca Mountain during Pleistocene pluvial conditions; (c) to compare postulated past climates based on properties of early Holocene and Pleistocene soils to paleoclimatic models that are reconstructed from other lines of evidence, such as paleolimnology and terrestrial paleoecology, as a check on these models; (d) to postulate past climates based on the depth, distribution, and quantity of pedogenic carbonate and other soil parameters; and (e) to quantify rates of soil development in specific climates for use as a dating tool for Quaternary deposits and ages of fault movements.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.5.1.4.2 - Surficial deposits mapping of the Yucca Mountain area. The objectives of this activity are to determine the distribution, age, genesis, soil properties, and physical properties of surficial deposits in the Yucca Mountain area; to evaluate the influences of climate and tectonics on the genesis of surficial deposits; to provide a map of surficial deposits for facility placement planning, geomorphic studies, tectonics studies, engineering property studies, and surface infiltration studies; and to determine the distribution of major concentrations of calcite-silica deposits at or near the ground surface at Yucca Mountain.

A section on the late Quaternary history of surficial deposits at Yucca Mountain was prepared for inclusion in the climate synthesis report (Forester et al., in prep.). This section of the synthesis report focuses primarily on the record of fluvial processes operating in Fortymile Wash during the Quaternary, and on the paleoclimatic implications of the fluvial history of this major tributary to the Amargosa River. Many of the results of mapping and chronostratigraphic studies of the surficial deposits in and adjacent to Fortymile Wash are discussed in Progress Reports #13 (DOE, 1996j) and #14 (DOE, 1996b).

The exposed Quaternary history of Fortymile Wash is characterized by the development of a large alluvial fan extending into the central Amargosa Desert (see Figure 3-1), by incision of the upper part of the fan before the last glacial maximum, and by the overlapping stratigraphic relations of younger alluvial sediments. These relationships suggest that aggradation took place during the transitional climates into and out of glacial periods as a consequence of higher intensity rainfall and runoff that resulted in increased erosion of the adjacent hillslopes and an abundant supply of sediment to the fluvial system. Conversely, incision occurred during wet and

cold periods when streamflow was persistent and slopes were stabilized by vegetation, thereby reducing the available sediment supply. One large episode of aggradation has been dated between 120 ka and 50 ka. The incision of the upper part of the alluvial fan seems likely to have occurred about 50 ka to 25 ka. Other episodes of aggradation occurred during the transition to the Holocene (about 15 to 8 ka) and again in later Holocene time. The spatial and temporal relations of the various surficial units, as well as fan incision, are therefore considered to be a record of wet and dry periods in the area and to indicate periods of perennial or at least seasonally sustained flow through Fortymile Wash.

Activity 8.3.1.5.1.4.3 - Eolian history of the Yucca Mountain region. The objectives of this activity are to document eolian erosion and deposition in the Yucca Mountain area during the last 750,000 years; to determine paleoenvironmental conditions during times of eolian deposition and intervening times of surface stability and soil formation; and to determine source areas of sand and silt.

No progress was made during the reporting period; this was an out-year activity.

Forecast: No activity is planned for this study during FY 1997.

3.4.5 Study 8.3.1.5.1.5 - Paleoclimate-Paleoenvironmental Synthesis

The objective of this study is to compare the paleoclimate estimates from the various proxy data sets and provide data synthesis in the formats required for future climate and paleohydrology investigations.

The climate synthesis report (Forester et al., in prep.) describes the results, interpretations, and conclusions of the investigations conducted within the site characterization climate and Quaternary hydrology programs. A major conclusion drawn from the large and varied data sets that have been collected is that the combined data are compatible and do not lead to inconsistent interpretations.

The major insolation-controlled climate cycle is 400 ky in duration with subcycles of approximately 100 ky (Berger and Loutre, 1991). Climate change occurs because changes in insolation, which is the major millennial scale forcing function in the climate system, affects the way the atmospheric heat budget is balanced. The water-table flow system has risen about 100 m in response to changes to cooler and wetter periods during the last two glacial cycles. The next glacial cycle, if it is similar to the cycle from 400 to 350 ka as expected, will not be as cold or as wet as the last two cycles.

Forecast: Climate estimates from the last glacial period (40 ka to 10 ka) will be refined using both aquatic and terrestrial climate records and the results from a workshop on climate. A climate-linked vegetation data base (USGS Global Change Program) will be used to develop Project-suggested climate scenarios from data collected by the Desert Research Institute and other sources of packrat-midden data. The scenario results, and results obtained by other

methods applied to terrestrial and aquatic data, will be evaluated by the panel members, who will arrive at a consensus consisting of one or more scenarios. The consensus will be used to provide climate-parameter output in any format desired by other Project participants. The output would include mean annual precipitation and temperature values, as well as other values such as degree-days or effective-moisture levels for various episodes within the last glacial period.

Owens Lake data will be transformed into climate parameters using aquatic paleontologic- and isotopic-climate proxies. The climate parameters from Owens Lake during the last glacial cycle will be compared with results from the just described study, and those data will be used to produce the climate estimates for the full 400 ky record. The climate estimates from the 400 ky record will then be available for other Project participants and will provide data-based criteria for establishing probable climate boundary conditions for the next 100 ky.

A peer-reviewed journal article or USGS Open-File Report will be prepared that incorporates results from the refinement studies described earlier (including appropriate additions of data collected in FY 1997) and integrates those results with the climate synthesis report completed during FY 1996 (Forester et al., in prep.). The revised synthesis report will emphasize those past extreme climate conditions that, should they occur in the future, could impact the performance of a potential repository at Yucca Mountain. The revised synthesis report will include estimates or upper bounds of mean annual precipitation that accompanied these extreme past climate conditions, and uncertainties in these estimates. The synthesis will entail interpretation of a large amount of paleontologic, stratigraphic, geochronologic, and stable- and radiogenic-isotopic data, including relevant data, information, interpretations, and scenarios from sources outside of the Project. The data and report will be organized and presented to be directly usable in regional and site-scale hydrologic models and by performance assessment.

3.4.6 Study 8.3.1.5.1.6 - Characterization of the Future Regional Climate and Environments

The objective of this study is to evaluate climate parameters for local Yucca Mountain scenarios over the next 100,000 years, with emphasis on the next 10,000 years for local climate scenarios that are both reasonably probable and relevant to repository performance.

Activity 8.3.1.5.1.6.1 - Global climate modeling. The objectives of this activity are to identify a set of global climate states (global boundary conditions) that are reasonably likely to occur over the period of concern, that are relevant to system performance, and that are pertinent to understanding global climate effects; and to use one or more carefully chosen global general circulation models with these selected global climate states to provide time-dependent boundary conditions for use as input to regional models.

With the selection and qualification of the modeling codes reported in Progress Report #13 (DOE, 1996j), and the preliminary identification of modeling states defined in the study plan, this activity is considered complete.

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Activity 8.3.1.5.1.6.2 - Nested global-regional climate modeling. The objective of this activity is to embed higher-resolution regional climate modeling within global climate modeling to develop a capability to model future climate-induced conditions for use in modeling net future infiltration in the Yucca Mountain area.

Evaluation and validation of the nested climate model was completed, and this activity is considered complete.

Activity 8.3.1.5.1.6.3 - Site-specific model output adjustment. The objective of this activity is to predict climatic parameters such as precipitation, soil moisture, and net infiltration rates for several possible future climate scenarios at Yucca Mountain.

The relevant aspects of this activity, originally planned as part of the future climate modeling study, are presently being addressed by the infiltration and unsaturated hydrologic modeling studies (Studies 8.3.1.2.2.1 and 8.3.1.2.2.9, Section 3.1.5 and Section 3.1.15, respectively of this progress report). Activity 8.3.1.5.1.6.3 is therefore considered complete.

Activity 8.3.1.5.1.6.4 - Future climate synthesis. The objective of this activity is to analyze time-series data of climatic variability based on the paleoclimatic record to identify possible future scenarios of concern that may occur during the next 100,000 years.

Modeling of a potential future "greenhouse" climate state, with carbon dioxide concentrations twice that of the current climate, was completed.

Forecast: Modeling of a potential future climate state considered most important to modeling of future hydrology will be completed in FY 1997. Under the schedule and scope associated with the viability assessment, the documentation of the FY 1997 modeling work will complete this study.

3.4.7 Study 8.3.1.5.2.1 - Characterization of the Quaternary Regional Hydrology

The objective of this study is to characterize the distribution of surface water, the unsaturated zone infiltration and percolation rates, and the ground-water potentiometric levels during the Quaternary in the vicinity of Yucca Mountain.

Activity 8.3.1.5.2.1.1 - Regional paleoflood evaluation. The objectives of this activity are to identify the locations and investigate the hydraulic characteristics of paleoflood events and compare this evidence with the locations and characteristics of modern flooding and geomorphic processes; and to assess the character and severity of paleoflood and debris hazards and the potential of flood and debris hazards for the repository during the preclosure period.

No progress was made during the reporting period; this was an out-year activity.

Activity 8.3.1.5.2.1.2 - Quaternary unsaturated zone hydrochemical analysis. The objectives of this activity are to determine the past infiltration and percolation history at Yucca Mountain by analyzing the isotopic and chemical characteristics of water from the unsaturated zone; and to understand the past unsaturated zone hydrologic system by modeling vadose water hydrochemistry to help predict the future hydrologic system.

The scope of this work was transferred to Activity 8.3.1.2.2.7.2 (Section 3.1.11 of this progress report).

Activity 8.3.1.5.2.1.3 - Evaluation of past discharge areas. The objectives of this activity are to determine the location, type, and extent of hydrogeologic units in the ground-water discharge areas of the Amargosa Desert and Death Valley; to understand the past quantity and quality of water in the discharge areas of Franklin Lake, Amargosa River, and Peter's Playa and to determine the paleohydrologic significance of Peter's Playa and Franklin Lake as discharge areas; to determine the location and hydrogeologic characteristics of paleospring deposits in the discharge area; to determine the location and amount of discharge by evapotranspiration that has occurred at past discharge sites; to understand the past and present discharge areas of the regional hydrologic system to predict the future saturated zone hydrologic system at Yucca Mountain; and to determine past ground-water levels in carbonate caverns as evidence of past hydrologic conditions.

Past ground-water discharge and late Pleistocene fluctuation in water table elevations were described for inclusion in the climate synthesis report (Forester et al., in prep.). This description focuses on the characteristics and geochronology of paleodischarge deposits exposed in southern Crater Flat and the central Amargosa Desert (see Figure 3-1). These surface deposits are down gradient from, and within 15 to 20 km of, Yucca Mountain. These deposits provided information to determine the maximum extent and timing of past water-table fluctuations that are important aspects for estimating the possible range of saturated zone conditions beneath Yucca Mountain over the next several glacial cycles. In addition, paleohydrologic information from the saturated zone provided insight about how rapidly ground-water hydrologic systems responded to changes in Pleistocene climate and indirectly may delineate changes in areas of significant recharge, flow paths, and travel times.

Combined isotopic evidence suggests that discharging water at paleospring sites represents regional ground waters rather than local perched systems. This means that the regional water table elevation fluctuated in the past as a response to the availability of higher effective moisture during periods of wetter climates. One of the main results of the studies of paleodischarge deposits is recognition that regional water table elevations were commonly higher by as much as 100 m during the last two glacial cycles (60 to 10 ka and 170 to 100 ka) (Study 8.3.1.5.1.5, Section 3.4.5 of this progress report). Several important conclusions can be made:

1. The close correspondence between climate records and discharge records imply rapid responses, probably within a few millennia, of the water table to climate change. Within the limitations of the chronology, no apparent lag was found between the time that water becomes available at the surface and the time when it is observable at

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discharge sites. This indicates rapid readjustment to increased levels of recharge and translation of the increased recharge down gradient to points of discharge.

2. Much of the late Pleistocene was characterized by higher water table elevations. Higher water table elevations could be normal consequences of Pleistocene climate conditions and the lower water table elevations observed today may be only typical of the relatively short, anomalously dry interglacial periods.
3. Multiple climate cycle histories are recorded at paleodischarge sites. Therefore, water table elevations are likely to rise during subsequent future pluvial cycles, and discharge will again be active.

Activity 8.3.1.5.2.1.4 - Analog recharge studies. The objective of this activity is to estimate the conditions and rates of ground-water recharge (infiltration) during the Quaternary Period in the vicinity of Yucca Mountain.

This activity was terminated in FY 1994; see Progress Reports #10 (DOE, 1994e) and #11 (DOE, 1995i) for details.

Activity 8.3.1.5.2.1.5 - Studies of calcite and opaline silica vein deposits. The objective of this activity is to determine the ages, distribution, origin, and paleohydrologic significance of calcite and opaline silica deposits along faults and fractures in the vicinity of Yucca Mountain.

The results of studies of low-temperature secondary deposits, notably calcite and opal, in open fractures and cavities in the volcanic rocks at Yucca Mountain, are discussed in a section on stable isotope geochemistry and mineralogy that was prepared for inclusion in the climate synthesis report (Forester et al., in prep.). These studies focused primarily on oxygen, carbon, and strontium isotopes as a means for determining the nature, origin, and age of the percolating waters from which the secondary deposits were precipitated. The ESF, in particular, provided a unique opportunity to study and sample calcite and opal deposits in fresh exposures. Because many of the specific details of the sampling and analytical programs conducted have been included in previous progress reports, only summary statements of results and current interpretations are given here:

1. The isotopic record provides clear evidence that the secondary minerals were deposited by meteoric waters percolating downward through the surficial deposits and Tertiary volcanic rocks of Yucca Mountain, as detailed in several of the items listed below.
2. The $\delta^{13}\text{C}$ record, which reflects the predominant plants growing in soils subject to infiltration, suggests that most of the $\delta^{13}\text{C}$ isotopic values fall within the range of plants that commonly live in relatively cool climates.
3. The $\delta^{18}\text{O}$ data from unsaturated zone calcite deposits show a range of values that become systematically lower with depth. The reduction in values with depth reflects the temperature dependence of the fractionation of $\delta^{18}\text{O}$ between water and calcite.

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The systematic nature of that decline implies that the present day thermal gradient has not obviously changed over at least the last 500 ky.

4. The $\delta^{18}\text{O}$ data appear to record an air mass isotopic signature that is weighted toward arctic to polar maritime precipitation sources consistent with glacial climates. These data also show a definite connection between the stable isotopic signature of calcites within the unsaturated zone and percolation from the surface.
5. The $\delta^{87}\text{Sr}$ values show the solute sources for the secondary mineral deposits to be derived from soil carbonates. These isotopic values from perched water bodies also indicate the influence of surface percolation.
6. Both the $\delta^{13}\text{C}$ and $\delta^{87}\text{Sr}$ values provide evidence that the water table below Yucca Mountain was as much as 80 to 100 m higher than it is today. This interpretation is consistent with evidence for a higher water table associated with paleodischarge deposits (Activity 8.3.1.5.2.1.3).
7. The youngest uranium-series age yet obtained on calcite and opal in fractures and lithophysal cavities in the ESF is 28.3 ka with an initial uranium-234 to uranium-238 ratio of 6.4. Younger ages with low initial ratios (1.4 to 1.8) would have been expected had these secondary minerals been deposited from waters moving downward along fast pathways.
8. Uranium and radiocarbon ages of secondary minerals within unsaturated zone fractures imply that deposition took place primarily in the glacial periods, when the climate was wetter and cooler than today.

Forecast: Field investigations at paleodischarge sites near Yucca Mountain (southern Crater Flat, Amargosa Desert, and Fortymile Wash fan toe) will be completed to identify and document stratigraphic sections that provide a framework of time-dependent depositional variations. Uranium-series disequilibrium, thermoluminescence, and radiocarbon dating will be performed on materials deposited from hydrogenic, eolian, and biogenic materials to establish a defensible chronology for this stratigraphic framework. Stable-isotope (carbon and oxygen) and radiogenic-isotope analyses (strontium and uranium) will be performed on hydrogenic materials to establish origins of the ground waters and likely physical parameters. Samples of saturated zone ground water from wells up gradient from discharge sites in Crater Flat will be collected and analyzed. These will include resampling well USW VH-2 and wells in the upper reaches of Crater Flat (GEXA wells) for more comprehensive isotopic and dissolved-ion geochemistry. The water compositions will be speciated to determine whether existing ground-water compositions are consistent with the types of deposits at the discharge sites.

Work will continue to develop credible estimates of the flux history in the repository block using the age distribution and abundance of calcite and opal deposits occurring in fractures and cavities encountered in the ESF. The study will develop estimates of past temporal and spatial percolation flux and will include the construction of scenarios describing the nature of the

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percolation with respect to variable climate input at the surface. Demonstration of a buffered or sluggish response to changing surficial conditions would be considered a very positive attribute of the site with regard to water flux through the repository block. To evaluate the connection between mineral deposition in fractures and cavities with surficial processes, tracer isotope (oxygen, carbon, strontium and uranium) studies of calcite and opal will be continued in parallel with the isotopic dating. Establishing a credible time framework of deposition will continue to use high-precision thermal ionization mass spectrometric uranium-series dating with emphasis on minimal subsample sizes to maximize age resolution. The system thorium-230/radium-226 will be used to better constrain the depositional model used to interpret the ages. The work will be extended to include high-precision uranium-lead dating of opal occurrences embedded throughout the calcite fracture and cavity fillings to establish depositional rates of the calcite for input to the flux calculations. Preliminary analyses have already demonstrated the feasibility of dating the older opals by the uranium-lead method. Samples will be collected and analyzed from the southern part of the ESF main drift and from the south ramp. Samples collected along the south ramp will provide improved understanding of the nature and rates of percolation through the Tiva Canyon Tuff and the role of the PTn in controlling percolation through the Topopah Spring Tuff. Detailed line surveys will be conducted in concert with sample collection to provide quantitative determinations of the abundance of calcite and opal in the TSw2 horizon as intersected by the ESF.

All existing geochronologic and isotopic data for the potential repository block, including but not limited to uranium-series, chlorine-36, carbon-14, uranium-lead, and tritium, will be compiled and interpreted. A comprehensive report will be prepared on the results of these studies, and the results will be used to develop credible estimates of the flux history in the repository block.

3.4.8 Study 8.3.1.5.2.2 - Characterization of the Future Regional Hydrology Due to Climate Changes

The objective of this study is to characterize impacts of potential future climate changes on site unsaturated zone hydrology and regional and site surface-water system and saturated zone hydrology.

Activity 8.3.1.5.2.2.1 - Analysis of future surface-water hydrology due to climate changes. The objectives of this activity are to simulate past changes in runoff and surface-water storage (lakes) resulting from past climatic change; and to use the relationship between paleoclimate and paleosurface-water conditions to predict the impact of future climatic conditions on the surface-water hydrology at the site.

No progress was made during the reporting period; this was an out-year activity.

Activity 8.3.1.5.2.2.2 - Analysis of future unsaturated zone hydrology due to climate changes. The objective statement for this activity has been deleted.

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As reported in Revision 9 of the Site Characterization Program Baseline (DOE, 1995g), this activity has been deleted; the scope of work will be performed under Activity 8.3.1.2.2.9.5 (Section 3.1.13 of this progress report). See Appendix H for the Site Characterization Program Baseline history.

Activity 8.3.1.5.2.2.3 - Evaluation of possible future changes of the climate and regional geologic framework on the regional saturated zone hydrology. The objectives of this activity are to reconstruct paleohydrologic conditions at Yucca Mountain and use these conditions together with the paleoclimatic conditions reconstructed as a basis to predict the impact of future climatic conditions on the saturated zone hydrologic system; to synthesize the existing paleohydrologic data through the use of numerical simulation techniques to determine effects that greater recharge would have on water-table altitude, ground-water flow paths, and hydraulic gradients between Yucca Mountain and the accessible environment; and to evaluate possible regional tectonic and thermal events that may produce prolonged or transient effects on the regional water level.

No progress was made during the reporting period; this was an out-year activity.

Forecast: No activity is planned for this study during FY 1997.

3.5 EROSION (SCP SECTION 8.3.1.6)

The changes to the Erosion Program since the SCP was issued are summarized in Appendix A, Section A.1.5.

The scope of work envisioned for the erosion studies has been completed. As a result of the study plan work scope consolidation effort, no study plans were developed in this program. During the previous reporting period, the NRC provided the DOE with an Issue Resolution Status Report that described the basis for the NRC determination that adequate information existed to close all the open items associated with this issue (NRC, 1996c). [See Progress Report #14 (DOE, 1996b)].

Forecast: No further work is planned for the Erosion Program.

3.6 POSTCLOSURE TECTONICS (SCP SECTION 8.3.1.8)

Changes to the Postclosure Tectonics Program since the SCP was issued are summarized in Appendix A, Section A.1.7.

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3.6.1 Study 8.3.1.8.1.1 - Probability of Magmatic Disruption of the Repository

The objective of this study is to assess the probability of future magmatic activity with respect to siting of a potential repository for the storage of high-level radioactive waste at Yucca Mountain.

Activity 8.3.1.8.1.1.1 - Location and timing of volcanic events. The objective of this activity is to synthesize the data collected by other activities on the dating, location, and volume of late Cenozoic volcanic events in the region surrounding the site.

No funding was provided for this activity during FY 1996. However, a compilation of latitude, longitude, Mercator projections, elevations, age and volume (of selected centers) was provided in the summary and synthesis report for this study (Crowe et al., in prep.).

Activity 8.3.1.8.1.1.2 - Evaluation of the structural controls of basaltic volcanic activity. The objective of this activity is to investigate the time-space patterns of past volcanic activity in the Yucca Mountain region and the possible structural controls of volcanic centers and potential future centers at and adjacent to Yucca Mountain.

Project volcanologists incorporated spatial and structural models used by the expert judgment panel on volcanism as part of the Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada (CRWMS M&O, 1996j) into chapter 3 of the summary and synthesis report for this study (Crowe et al., in prep.). A table that summarized alternative structural and spatial models for the post-4.7 Ma basalt centers of the Yucca Mountain region was prepared. New work on tectonic models of the Crater Flat basin was also summarized in the report. Revised geophysical data for the Yucca Mountain region were incorporated into the report, including the results and interpretations of the seismic reflection and refraction line across Crater Flat and Yucca Mountain and seismic and teleseismic data from the upgraded seismic network with data from the Little Skull Mountain earthquake. The former data support the interpretation that detachment and caldera models are not important for the Yucca Mountain region, and this interpretation was incorporated into discussions of tectonic controls of sites of basaltic volcanic centers in the summary and synthesis report.

Activity 8.3.1.8.1.1.3 - Presence of magma bodies in the vicinity of the site. The objective of this activity is to review geophysical and geochemical data collected in the vicinity of the site to assess whether there are any indications of the presence of crustal magma bodies that could be the source of future volcanic activity.

A summary of teleseismic data from the upgraded seismic net was incorporated into Chapter 3 of the summary and synthesis report for this study (Crowe et al., in prep.). Data are preliminary but show that the magnitude of the teleseismic low velocity signal identified by Evans and Smith (1992), may be an artifact of the domain depths used in data reduction. At least some of the teleseismic delays may be attributed to relatively shallow structural features, and the data reduction methods of Evans and Smith (1992) may artificially increase the amplitudes of teleseismic anomalies.

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Activity 8.3.1.8.1.1.4 - Volcanism probability studies. The objective of this activity is to revise the estimates of the probability of volcanic disruption of a repository site at Yucca Mountain, incorporating newly acquired data on the age, location, and volume of volcanic centers in the Nevada Test Site region and the results from activities investigating the possibility of structural controls of sites of volcanic activity and the presence of magma bodies in the Yucca Mountain area. These data may result in modifications of the area ratio and the rate of volcanic activity used in the probability formula.

A report was completed that documents the results of the Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada (CRWMS M&O, 1996j). The objectives of this project were to assess the probability of disruption by a volcanic event of the proposed high level waste repository at Yucca Mountain and to quantify the uncertainties associated with this assessment. For this study, disruption is defined as the physical intersection of magma with the potential repository volume; volcanic event includes both eruptive and intrusive features; and probability is defined as an annual frequency. The results of the Probabilistic Volcanic Hazard Analysis are that the aggregate expected annual frequency of intersection of the potential repository footprint by a volcanic event is 1.5×10^{-8} . The major contributors to the uncertainty in the frequency of intersection are statistical uncertainty in estimating the rate of volcanic events from small data sets and the uncertainty in modeling the spatial distribution of future events.

Cumulative probability distributions were developed for the event counts of post-4.7 Ma basalt centers in the Yucca Mountain region using Latin Hypercube simulation modeling that incorporated data from the volcanism expert judgment study completed as part of the Probabilistic Volcanic Hazard Analysis. Intervals of 1.1 and 4.8 Ma were used to revise and assess the sensitivity of recurrence rates. Sensitivity studies of the probability of magmatic disruption of a repository and repository system were completed by assessing the results of simulation modeling where volcanic events were assigned dimensions of basaltic feeder dikes. This approach was applied to two different repository areas and a repository system defined to be an effect area from intrusion of a basaltic dike. The results show that the disruption ratio is related systematically to the area and geometry of volcanic zones and a critical intersection volume. Simulation modeling was used for sensitivity studies of the recurrence rate and the disruption ratio for specific volcanic zones, and the modeling incorporated considerations of undetected volcanic events using data from the expert judgment study. An assessment was completed of the sensitivity with respect to probabilistic volcanic hazard analysis of uncertainty in the location of the east-northeast boundaries of volcanic zones. The potential effect on probabilistic assessments of not studying the aeromagnetic anomalies of the Amargosa Valley area were evaluated. Sensitivity studies of radiological releases associated with both subsurface effects and eruptive effects on a repository or repository system show very limited impacts and are consistent with past studies of total system performance assessment. All these data were incorporated into Chapter 6 of the summary and synthesis report (Crowe et al., in prep.).

Forecast: No further work is planned for this study.

3.6.2 Study 8.3.1.8.1.2 - Physical Processes of Magmatism and Effects on the Repository

The objective of this study is to gather data on the potential effects of magmatic activity on the proposed repository. The data will be used to assess the consequences of such an eruption on repository performance.

Activity 8.3.1.8.1.2.1 - Eruptive effects. The objective of this activity is to determine the effects of hydrovolcanic, Hawaiian, Strombolian, and violent Strombolian eruptions of basaltic magma on a repository. The results will be available for use in performance assessment calculations of possible radiological releases.

Data on the quantity of wall-rock debris entrained by rising magma and erupted onto the surface of the earth from volcanoes in the Lucero and San Francisco volcanic fields (New Mexico and Arizona, respectively) were reported in the summary and synthesis report for this study (Crowe et al., in prep.). These data were collected from analog volcanoes and represent a range of eruption mechanisms including Strombolian, Hawaiian, and hydrovolcanic. Strombolian and Hawaiian eruptions generally entrain little wall rock material and are unlikely to strongly influence total system performance assessments. Hydrovolcanic eruptions entrain 1000 to 10,000 times more wall rock debris and could influence performance assessments, depending mainly on the probability of such eruptions.

Activity 8.3.1.8.1.2.2 - Subsurface effects of magmatic activity. The objective of this activity is to evaluate the subsurface effects of emplacement of basalt dikes and intrusive bodies through and adjacent to a potential repository. This study will assess the mechanisms of incorporating waste in magma, the geometry of basalt intrusions, and hydrothermal effects on waste isolation of basalt intrusions through or near a repository.

The summary and synthesis report for this study (Crowe et al., in prep.), presents field data from analog sites at which the feeder systems of small basaltic volcanoes are exposed, and where the volcanoes penetrated silicic tuffs similar to those at Yucca Mountain. Geometries of shallow intrusions were determined by a complicated interplay between pre-existing structures, shallow stress field variations, and rock mechanical properties. The intrusion geometry, in turn, determined the spatial pattern of alteration in the host rocks. Chemical and mineralogical studies of the host tuffs indicated that for shallow, small-volume basaltic intrusions alteration was limited to material within a few tens of meters of the intrusion. There is no evidence of development of extensive, long-lived hydrothermal systems. Numerical modeling studies suggested that the farthest reaching "hydrothermal" process in the vadose zone, convection of pore air, was limited to the area within 2.5 km of intrusions of relevant sizes.

Activity 8.3.1.8.1.2.3 - Magma system dynamics. The objectives of this activity are to evaluate the dynamics of basaltic magmatism, including tracing the processes of formation of basalt magma through generation in the mantle, ascent through the mantle and crust, potential storage in the mantle and crust, and eruption at the earth's surface.

The processes of magmatic activity from melt generation through storage, transport, and eruption are described in Chapter 5 of the summary and synthesis report for this study (Crowe et al., in prep.). These processes may be important for providing some "deterministic" constraints on probability calculations. Review of available data failed to identify the causes of the low magma-flux dynamics of the Yucca Mountain region.

Forecast: This study was terminated at the end of FY 1996. No further work is expected.

3.6.3 Study 8.3.1.8.2.1 - Tectonic Effects: Evaluations of Changes in the Natural and Engineered Barrier Systems Resulting from Tectonic Processes and Events

The objective of this study is to assess the probability and effects of tectonic processes and events that could result in adverse effects on waste package lifetime, average percolation flux rate over the repository, altitude of the water table, local fracture permeability, effective porosity, and rock geochemical properties.

Activity 8.3.1.8.2.1.1 - Analysis of waste package rupture due to tectonic processes and events. The objective of this activity is to collect and synthesize data that can be used to assess the probability and effects of tectonic processes and events that could result in adverse impacts on waste package lifetime and performance.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.8.2.1.2 - Analysis of the effects of tectonic processes and events on average percolation flux rates over the repository. The objective of this activity is to analyze and assess the probability and effects of tectonic initiating events that may result in changes in the average percolation flux rate at the top of the Topopah Spring welded hydrogeologic unit.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.8.2.1.3 - Analysis of the effect of tectonic processes and events on water-table elevation. The objective of this activity is to produce analyses and assessments of the probability that tectonic initiating events could result in significant changes in the elevation of the water table, changes in the hydraulic gradient, the creation of discharge points in the controlled area, or the creation of perched aquifers in the controlled area.

A report by Barr et al. (1996) presents data on perched water occurrences under Yucca Mountain, with emphasis on a water body encountered in boreholes (USW UZ-1 and USW UZ-14) located a few hundred meters northwest of the northwest corner of the potential repository and below the level of the potential repository. This water body may cover an area of as much as 100 acres (40.5 ha), may extend to within 100 m of the potential repository, and has an average saturated thickness of 40 ft (12.2 m). The saturated rock lies directly above the basal vitrophyre of the Topopah Spring Tuff, which retards downward percolation of water. Geologic relations suggest that (a) the perched water is partially confined laterally by a northeast-trending

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fault that lies between it and the potential repository, and (b) at some point the water flows southeastward across the fault and follows along the top of the east-dipping basal vitrophyre of the Topopah Spring Tuff which lies as close as 50 m to the floor of the repository at its western edge. The implication is that recharge of ground water from the higher and wetter northern part of Yucca Mountain is diverted southward into the area of the potential repository, resulting in a greater amount of water passing through the unsaturated zone beneath this area than might be expected from only normal recharge from the immediately overlying land surface.

Activity 8.3.1.8.2.1.4 - Analysis of the effects of tectonic processes and events on fracture permeability and effective porosity. The objective of this activity is to address possible changes in fracture permeability and effective porosity caused by tectonic events and processes.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.8.2.1.5 - Analysis of the effects of tectonic processes and events on rock geochemical properties. The objective of this activity is to provide assessments of the initiating events related to local changes in distribution coefficients resulting from tectonic processes and events.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Work under this study will be limited to providing support to the performance assessment group in developing and evaluating tectonic scenarios that have a potential to disturb the site and preparing a report describing the performance assessment work.

3.6.4 Study 8.3.1.8.3.1 - Analysis of the Effects of Tectonic Processes and Events on Average Percolation Flux Rates Over the Repository

The objective of this study is to produce analysis and assessments of the probability and effects of tectonic initiating events that may result in changes in the average percolation flux rate at the top of TSw2.

This study has been combined with Study 8.3.1.8.2.1 (Section 3.6.3 of this progress report).

Forecast: No further work is planned under Study 8.3.1.8.3.1.

3.6.5 Study 8.3.1.8.3.2 - Analysis of the Effects of Tectonic Processes and Events on Changes in Water-Table Elevation

The objective of this activity is to provide analyses and assessments of the probability that tectonic initiating events could result in significant changes in the elevation of the water table,

changes in the hydraulic gradient, the creation of discharge points in the controlled area, or the creation of perched aquifers in the controlled area.

This study has been combined with Study 8.3.1.8.2.1 (Section 3.6.3 of this progress report).

Forecast: No further work is planned under Study 8.3.1.8.3.2.

3.6.6 Study 8.3.1.8.3.3 - Analysis of the Effects of Tectonic Processes and Events on Local Fracture Permeability and Effective Porosity

The objective of this study is to address possible changes in fractures, or rock mass permeability and effective porosity caused by tectonic events and processes.

This study has been combined with Study 8.3.1.8.2.1 (Section 3.6.3 of this progress report).

Forecast: No further work is planned under Study 8.3.1.8.3.3.

3.6.7 Study 8.3.1.8.4.1 - Analysis of the Effects of Tectonic Processes and Events on Rock Geochemical Properties

The objective of this study is to provide assessments of the initiating events related to local changes in distribution coefficients resulting from tectonic processes and events.

This study has been combined with Study 8.3.1.8.2.1 (Section 3.6.3 of this progress report).

Forecast: No further work is planned under Study 8.3.1.8.4.1.

3.6.8 Study 8.3.1.8.5.1 - Characterization of Volcanic Features

The objective of this study is to provide data on the age, location, eruptive history, and volume of young volcanic rocks in the vicinity of the site. These data will be used to refine the calculations on the probability of igneous or volcanic events occurring in the controlled area and penetrating the repository.

Activity 8.3.1.8.5.1.1 - Volcanism drillholes. The objective of this activity is to investigate the origin of four or five aeromagnetic anomalies found in Crater Flat and the Amargosa Valley. Data from this work will be used to refine probability calculations, to refine geophysical models of the Yucca Mountain region, to evaluate the tectonic setting of volcanic

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centers, and to test concepts of the temporal and geochemical evolution of basalts in the Yucca Mountain region.

No progress was made during the reporting period. This is an unfunded activity that has been deferred indefinitely.

Activity 8.3.1.8.5.1.2 - Geochronology studies. The objective of this activity is to establish the chronology of basaltic volcanism and the youngest silicic volcanic activity in the Yucca Mountain region. These data will be used to revise the recurrence rate of the volcanic probability calculations and to determine the age of cessation of silicic volcanic activity. Further studies are required for three topics: (a) the age of the Quaternary volcanic events in the Yucca Mountain region; (b) the age and eruption chronology of the youngest (<0.5 Ma) volcanic event in the Yucca Mountain area; and (c) the age of the youngest silicic volcanic activity in the region with emphasis on the Black Mountain caldera or young silicic rocks that may be encountered in shallow volcanic drillholes.

Final geochronology data for the Lathrop Wells volcanic center were compiled and interpreted for inclusion in the summary and synthesis report (Crowe et al., in prep.). Argon-40/argon-39 whole-rock and sanidine data indicate that the Lathrop Wells center was formed at $\sim 75 \pm 10$ ka, with the possible exception of the youngest eruptive unit. Uranium-thorium disequilibrium data indicate that the youngest eruptive unit may be as young as ~ 50 ka. Previously, the "accepted age" of the Lathrop Wells center was about 300 ka, but data from various methods produced ages that ranged from about 140 ka to less than 20 ka. The new data decrease the probability that Lathrop Wells is polygenetic (Crowe et al., in prep. Chapter 2).

Activity 8.3.1.8.5.1.3 - Field geologic studies. The objective of this activity is to establish the field geologic relations and the eruptive history of basaltic volcanic centers in the Yucca Mountain region.

A revised geologic map of the Sleeping Butte volcanic centers was compiled on an orthophotographic base. This map provides basic geologic information about the Sleeping Butte centers for chapter 2 in the summary and synthesis report for this study (Crowe et al., in prep.) and other planned publications.

Trigonometric calculations based on data obtained from trenching studies in late FY 1995 indicate that ~ 4 to 5 m of scoria has been eroded from the rim of the main cinder cone at Lathrop Wells. This finding indicates that the cinder cone is more eroded than previously thought and suggests that the oldest helium-3 cosmogenic exposure age of ~ 63 ka obtained from the cone may reflect the approximate true age of the cone (Crowe et al., in prep., Chapter 2).

Activity 8.3.1.8.5.1.4 - Geochemistry of scoria sequences. The objective of this activity is to determine the geochemistry of scoria sequences of different ages at the Lathrop Wells center and older centers in the Crater Flat volcanic zone. The models will be used to test geologic assumptions made for the probability calculations and the time-space tectonic model for the distribution of basaltic volcanism. In addition, the data on the geochemistry of the scoria

sequences also will be used to correlate basaltic ash in fault trenches with their correct eruptive source.

Multielement trace-element modeling indicates that the unique composition of the Qs4 tephra deposit at Lathrop Wells resulted from pedogenic alteration of tephra most likely derived from the main cinder cone. This finding decreases the probability that this tephra deposit originated from a Holocene eruption at Lathrop Wells (Crowe et al., in prep., Chapter 4).

Modeling of fractional crystallization, magma mixing, or crustal assimilation processes was completed, and the results indicate that none of these processes can account for the geochemical variations observed at Lathrop Wells. A remaining hypothesis that has not been fully tested is that the geochemical variations at Lathrop Wells are caused by systematic changes in mantle melting conditions through time (Crowe et al., in prep., Chapter 4).

The geochemical composition of basaltic ash found in numerous fault trenches near Yucca Mountain indicates that the ash originated from Lathrop Wells and not from any other Quaternary volcanoes in the region. The age of the ash is therefore ~75 ka. Direct dating of ash from the Solitario Canyon fault yields an erroneously old age of ~900 ka, probably because of a small amount of sample contamination by rhyolitic glass of Miocene age (Crowe et al., in prep., Chapter 4).

Activity 8.3.1.8.5.1.5 - Geochemical cycles of basaltic volcanic fields. The objective of this activity is to determine the time-space geochemical variations of the volcanic fields of the southern Great Basin.

Major, trace-element, and isotopic data gathered before FY 1996 were synthesized for incorporation into chapter 4 of the summary and synthesis report for this study (Crowe et al., in prep.). This chapter contains discussions pertaining to the petrologic and geochemical constraints on basaltic volcanism.

Forecast: Further work on this study has been deferred indefinitely; no work is planned for FY 1997.

3.6.9 Study 8.3.1.8.5.2 - Characterization of Igneous Intrusive Features

The objective of this study is to gather data concerning the presence of thermal anomalies in the area and data on the geochemical and physical effects of intrusions on the surrounding rock. The evidence for the presence or absence of thermal anomalies will be used as part of the evaluation of the presence of significant magma bodies in the area and their relation to the probability of future volcanic events.

No progress was made during the reporting period; this was an unfunded study.

Forecast: No activity is planned for FY 1997.

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3.6.10 Study 8.3.1.8.5.3 - Investigation of Folds in Miocene and Younger Rocks of Region

The objective of this study is to establish the regional pattern and rate of Neogene folding.

This study contains one activity that relies on available data; no unique data are to be acquired. Therefore, no study plan will be developed.

Activity 8.3.1.8.5.3.1 - Evaluation of folds in Neogene rocks of the region. The objective of this activity is to establish the pattern, rate, amplitude, and wavelength of post-middle Miocene folding in the region.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No further work is expected in this study.

3.7 HUMAN INTERFERENCE (SCP SECTION 8.3.1.9)

Changes to the Human Interference Program since the SCP was issued are summarized in Appendix A, Section A.1.8.

The studies in this program are intended to assess the survivability of a long-term surface marker system, the natural resource potential, and the impacts of potential human activities in the foreseeable future that could affect the waste isolation capabilities of the site. The natural resource assessment includes metallic resources, water resources, industrial rocks and minerals, and energy resources (such as, oil, gas, coal, tar sands, geothermal energy, and uranium). Studies on the inadvertent human interference issue will evaluate the feasibility of a surface marker system that would warn future generations of a hazard and assess the potential for inadvertent human interference associated with exploration for or exploitation of natural resources.

No study plans were developed for this section. No unique data have been acquired by these studies.

3.7.1 Study 8.3.1.9.1.1 - An Evaluation of Natural Processes that Could Affect the Long-Term Survivability of the Surface Marker System at Yucca Mountain

The objective of this study is to provide information on the currently or potentially active natural processes at Yucca Mountain capable of adversely affecting the long-term survivability of the surface marker system. This study will synthesize data obtained from other activities to be undertaken in support of several investigations. Suitable locations of the monuments for the surface marker system will be determined.

Activity 8.3.1.9.1.1.1 - Synthesis of tectonic, seismic, and volcanic hazards data from other site characterization activities. The objective of this activity is to identify the potential locations of faulting and volcanic eruption or intrusion that could occur where they could affect the marker system.

The available information has been summarized and included in a report (Fehr et al., 1996) that describes the feasibility assessment for the permanent marker system. This feasibility evaluation did not reveal any natural process or site condition that would preclude the design, fabrication, and placement of a repository surface marker system for the Yucca Mountain site. The recommended locations for the markers are on bedrock, at higher elevations, and spaced such that adjacent markers are visible from each location.

Activity 8.3.1.9.1.1.2 - Synthesis evaluation of the effects of future erosion and deposition on the survivability of the marker system at Yucca Mountain. The objective of this activity is to determine the effects of future erosion and deposition on the topographic elements of the controlled area boundary at Yucca Mountain. The available information is being evaluated to identify the optimum locations for the markers.

Suggested locations for the surface markers were indicated on the map included in the feasibility report (Fehr et al., 1996).

Forecast: Additional data evaluation and probability studies will be completed as needed to support design of the permanent marker system.

3.7.2 Study 8.3.1.9.2.1 - Natural Resource Assessment of Yucca Mountain, Nye County, Nevada

The objective of this study is to identify and assess the natural resource potential at the proposed repository site at Yucca Mountain. The assessment will examine the present and foreseeable future resource potential of the controlled area in comparison with the surrounding area and the general geologic setting. The information and data obtained in this study will provide the basis for probabilistic calculations for evaluating the potential for inadvertent human interference.

The geochemical survey for the metallic resources study continued. The final documents (data) and records relating to the geothermal resources report were submitted to the records center. The oil and gas (petroleum) resources study was suspended, and final documents (data) and records relating to the industrial rocks and mineral resources report were submitted to the records center.

Activity 8.3.1.9.2.1.1 - Geochemical assessment of Yucca Mountain in relation to the potential for mineralization. The objective of this activity is to conduct a geochemical sampling program to evaluate the potential for precious, base, and strategic metals; energy resources; and industrial mineral resources in the vicinity of Yucca Mountain. Specific objectives include

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(a) selecting a suite of elements for analysis in a geochemical sampling program on the basis of known commodities that occur in silicic tuffs and/or trace elements indicative of commodities that occur in the tuffs, (b) developing a field program to include a systematic and biased sampling of surface materials, (c) generating a first-order geochemical data base for selected elements obtained from surface and subsurface sampling within the vicinity of Yucca Mountain, (d) evaluating the data base in conjunction with geological and geophysical data obtained from other site characterization activities to determine if additional data are needed for an evaluation of natural resources, and (e) evaluating the potential for the occurrence of natural resources in the vicinity of Yucca Mountain based on an analysis of the geochemical data.

Additional geochemical sampling was completed as part of the metallic resources activity (Activity 8.3.1.9.2.1.5). This sampling complements the sampling reported in Progress Report #14 (DOE, 1996b).

Activity 8.3.1.9.2.1.2 - Geophysical/geological appraisal of the site relative to mineral resources. The objective of this activity is to qualitatively evaluate the available geophysical data base as it relates to Study Plan 8.3.1.9.2.1. Geologic models derived from geophysical data will be evaluated for their impact on mineral resources.

The geologic appraisal of the site and comparing of the site geology with the regional geology continued. Field work during the period included examining drill cores and cuttings from ten drillholes at Yucca Mountain. Examinations and limited sampling of selected mines in the region (Barrick Bullfrog, Sterling, and Barrick-Betze) was completed.

Activity 8.3.1.9.2.1.3 - Assessment of the potential for geothermal energy at Yucca Mountain, Nevada. The objective of this activity is to evaluate regional ambient heat flow and local heat flow anomalies. This activity assesses the geothermal regime in terms of its energy resource potential for either hydrothermal or conductive reservoir thermal systems.

This activity was reported as completed in Progress Report #14 (DOE, 1996b, p. 3-111).

Activity 8.3.1.9.2.1.4 - Assessment of hydrocarbon resources at and near the site. The objectives of this activity are to determine the potential for the presence or absence of suitable source rocks, reservoir rocks, and traps and seals at or near the site; to determine the potential for occurrence of conventional hydrocarbon resources (crude oil and natural gas) at and near the site; and to provide necessary data for the overall mineral and energy resource assessment to be performed.

The geology of oil-producing areas in Railroad Valley (in northeastern Nye County about 200 km northeast of Yucca Mountain) were evaluated as a possible basis for comparison with the area surrounding the potential repository site. A report (Grow et al., in prep.) analyzes fault geometries near the Kate Springs and Grant Canyon fields, using interpretations of a grid of four northwest-southeast and three north-south regional seismic lines. These lines show a north to south transition from shallow, moderate- to high-angle, west-dipping normal faults in the vicinity of the Kate Springs oil field, in east-central Railroad Valley, to a low-angle (<30°) fault system

in the vicinity of the Grant Canyon oil field in southeastern Railroad Valley. Both fields produce oil from Paleozoic and Mesozoic strata that lie beneath 3000 to 5000 ft (900 to 1500 m) of late Tertiary valley fill. The primary source rocks are the Chainman Shale of Mississippian age and Sheep Pass Formation of Late Cretaceous-early Tertiary age. The petroleum accumulations in these two fields, as well as in the other six fields in the valley, have been sealed by the unconformity at the base of Miocene valley fill deposits. The accumulations in the prolific Grants Canyon field occur above the low-angle fault.

Activity 8.3.1.9.2.1.5 - Mineral and energy assessment of the site, comparison to known mineralized areas, and the potential for undiscovered resources and future exploration. The objective of this activity is to integrate the data and information collected from the geochemical assessment, geophysical/geologic assessment, geothermal energy assessment, and hydrocarbon assessment.

Work during the period focused on completing the geochemical appraisal of Yucca Mountain. The results of this appraisal are essential components of the mineral resources evaluation. No progress was made on the site energy assessment; this was an unfunded activity.

Forecast: Geochemical analysis work will be completed. The final report on hydrocarbon resources is scheduled for FY 1997. The report will synthesize data on the hydrocarbon resources at the site and assess the oil and gas potential of the site. The potential for undiscovered hydrocarbon resources in the controlled area will be estimated by comparing the site geology and geochemistry with those of deposit models and with areas in the region that contain known deposits in similar geologic settings.

A final assessment of the potential for natural resources will be completed using site-specific data compared with regional geologic data and models of resource deposit genesis. Assessments of the metallic resources, oil and gas resource potential, miscellaneous energy resources, and water resources of the site will be combined with previously completed assessments of industrial rocks and minerals and geothermal resources.

A natural resources synthesis report will integrate geological, geophysical, and mineralogical information from the literature with data from the site, including new geological and geochemical data from Yucca Mountain and areas of known mineralization in the region. Potential for undiscovered deposits in the controlled area will be evaluated by comparing its geology and geochemistry with those of mineral deposit models and with areas in the region that contain known metal deposits in similar geologic settings. Completion of the natural resources synthesis report will conclude the studies planned in the SCP for natural resources.

3.7.3 Study 8.3.1.9.2.2 - Water Resource Assessment of Yucca Mountain, Nevada

The objective of this study is to use available data to estimate the future supply, demand, and value of the ground-water resource proximal to Yucca Mountain.

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Activity 8.3.1.9.2.2.1 - Projected trends in local and regional ground-water development and estimated withdrawal rates in southern Nevada, proximal to Yucca Mountain. The objectives of this activity are to assess the current and projected supply and demand situation in the foreseeable future for ground water in the geohydrologic study area and to estimate the value of the ground-water resource.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: The final report on the availability, quality, potential uses, and demand for water resources in the area of the Yucca Mountain site is scheduled to be completed in February 1997.

3.7.4 Study 8.3.1.9.3.1 - Evaluation of Data Needed to Support an Assessment of the Likelihood of Future Inadvertent Human Intrusion at Yucca Mountain as a Result of Exploration and/or Extraction of Natural Resources

The objective of this study is to compile and analyze data to assess the likelihood of inadvertent human interference in the Yucca Mountain vicinity.

Because no unique data were to be acquired by this study, no study plan was developed.

Activity 8.3.1.9.3.1.1 - Compilation of data to support the assessment calculation of the potential for inadvertent human intrusion at Yucca Mountain. The objectives of this activity are to determine the maximum drilling density and frequency (drillholes per square kilometer per 10,000 years) that can be reasonably assumed for a repository at Yucca Mountain; and to determine the extent to which future ground-water withdrawals will modify the expected ground-water flow paths.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Potential human activities within the controlled area that could affect waste isolation capabilities of the site, such as exploration drilling, will be assessed in a final report on natural resources.

3.7.5 Study 8.3.1.9.3.2 - An Evaluation of the Potential Effects of Exploration for, or Extraction of, Natural Resources on the Hydrologic Characteristics at Yucca Mountain

The objective of this study is to assess, in qualitative or quantitative terms, the effects of exploiting natural resources known or believed to be present at Yucca Mountain. Consideration of the effects of resource exploitation or extraction are limited to changes in the hydrologic, geochemical, and rock characteristics.

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No unique data are to be acquired by this study; thus, no study plan was developed.

No progress was made during the reporting period; this was an unfunded study.

Activity 8.3.1.9.3.2.1 - An analysis of the potential effects of future ground-water withdrawals on the hydrologic system in the vicinity of Yucca Mountain. The objective of this activity is to determine the potential effects of future ground-water withdrawals on the hydrologic system at Yucca Mountain. Effects of the withdrawals will be defined qualitatively and quantitatively.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.9.3.2.2 - Assessment of initiating events related to human interference that are considered not to be sufficiently credible or significant to warrant further investigation. The objective of this activity is to demonstrate that those initiating events that have been identified (Table 8.3.1.9-1, SCP) for the human interference issue are not considered sufficiently credible or significant to necessitate additional investigation.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. The inputs to computer modeling for varying water withdrawal assumptions and input bounds will be supplied under Study 8.3.1.9.2.2, which will be reported in the water resources final report.

3.8 METEOROLOGY (SCP SECTION 8.3.1.12)

Changes to the Meteorology Program since the SCP was issued are summarized in Appendix A, Section A.1.9.

Four studies and one investigation in the Meteorology Program (8.3.1.12) include work to describe current local and regional meteorological conditions. Three of the studies (8.3.1.12.1.1, 8.3.1.12.1.2, and 8.3.1.12.4.1) and the investigation (8.3.1.12.3) are controlled by the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b) and the Nevada Work Instruction: "Acquisition and Analysis of Regional Meteorological Data." The fourth study, Meteorological Data Collection at the Yucca Mountain Site (8.3.1.12.2.1), is controlled by the corresponding study plan.

3.8.1 Study 8.3.1.12.1.1 - Characterization of the Regional Meteorological Conditions

The major objective of this study is to collect and analyze meteorological data from various locations surrounding Yucca Mountain and to characterize the regional meteorology needed for site characterization performance assessment and design. This characterization will provide a regional overview of wind flow patterns and other parameters (primarily related to

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atmospheric dispersion and surface facility design) associated with meteorological conditions at Yucca Mountain. For additional descriptions of the objectives, refer to the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b).

Accomplishments during this period include identification, compilation, and initial analyses of data from the 23 meteorological monitoring stations operated by the National Oceanic and Atmospheric Administration, Air Resources Laboratory, Special Operations and Research Division (NOAA/ARL/SORD) on and around the Nevada Test Site. Special Operations and Research Division staff are preparing additional data summaries for use in the regional meteorology study. Work products, including data summaries prepared by the Special Operations and Research Division staff, are being used in the regional meteorological study.

Forecast: The literature compilation and data acquisition portions of the investigation will be continued during the analysis portion of this study. The information collected will be analyzed to respond to performance assessment and design information needs. Reports on current climatic conditions and climatic data needed for engineering design are planned for the next reporting period. A report on the regional wind patterns is scheduled for preparation next reporting period.

3.8.2 Study 8.3.1.12.1.2 - Plan for Synthesis of Yucca Mountain Site Characterization Project Meteorological Monitoring

The objective of this study is to develop a plan that provides for the coordination of meteorological monitoring efforts by various Project participants during site characterization.

The work in this study was combined with other studies in the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b) (see Section 3.8 of this progress report).

Forecast: Future work on this study will be controlled through Study 8.3.1.12.1.1 (see Section 3.8.1 of this progress report).

3.8.3 Study 8.3.1.12.2.1 - Meteorological Data Collection at the Yucca Mountain Site

The primary objective of this study is to provide site-specific data to resolve design and performance issues associated with preclosure radiological safety, including estimating potential radiological dosage related to repository operations. Data from this study are also used to respond to air quality permit requirements of the State of Nevada covering site characterization activities.

Activity 8.3.1.12.2.1.1 - Site meteorological monitoring program. The objective of this activity is to collect meteorological data at potential locations of surface facilities and at sufficient additional locations to characterize the meteorological conditions, including wind flow patterns and atmospheric dispersion characteristics, in the vicinity of Yucca Mountain.

The meteorological monitoring program continued at the nine active sites. Data on site design and radiological dose estimates were supplied to the design and environmental groups.

The 1995 summary report on the meteorological monitoring results (CRWMS M&O, 1996k) was published during the reporting period. The report includes a detailed description of the monitoring program, extensive climatological summary tables, discussions of annual trends, and references to the electronic data base. Wind data show the strong influence of topography on both wind direction and wind speed patterns and on the regular day and night distinct wind and atmospheric stability cycles. Precipitation data indicated that 1995 was the wettest of the ten years monitored by this study, primarily because of exceptionally large precipitation amounts early in the year.

Data from the monitoring network were included in the two quarterly ambient air monitoring reports submitted to the State of Nevada during the reporting period. These reports fulfill requirements of the State Air Quality Permit (No. AP9611-0573) required for continuing site disturbing activities. No significant increase in inhalable particulate matter (PM_{10}) concentration was noted during the reporting period, although the number of surface-disturbing activities increased.

Activity 8.3.1.12.2.1.2 - Data summary for input to dose assessments. The objective of this activity is to process the collected meteorological data into a format and content that will be useful in assessing radiological impacts, as required by design and performance issues.

No progress was made during the reporting period; this was an out-year activity.

Forecast: Data collection and reporting will continue at the nine monitoring stations. The data formatting activity will be performed once the airborne radiological impact assessment method has been determined.

3.8.4 Investigation 8.3.1.12.3 - Studies to Provide Data on the Location of Population Centers Relative to Wind Patterns in the General Region of the Site

The objective of this investigation is to provide data on wind flow patterns in the general region of Yucca Mountain. These patterns are needed to identify areas that could be impacted by airborne radiological material released from surface or underground facilities at Yucca Mountain.

The work in this study was combined with other studies in the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b) (see Section 3.8 of this progress report).

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Forecast: Future work on this study will be controlled and tracked through Study 8.3.1.12.1.1, discussed in Section 3.8.1 of this progress report.

3.8.5 Study 8.3.1.12.4.1 - Characterize the Potential Extreme Weather Phenomena and Their Recurrence Intervals

The objective of this study is to evaluate existing historical meteorological and climatological records, technical publications, and other relevant information to quantify the extreme weather phenomena that may be expected at the Yucca Mountain site and to determine their recurrence intervals.

This study analyzes existing meteorological data and technical publications to estimate the potential for occurrences and types of extreme weather events that might affect repository operations. The work in this study was combined with other studies in the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b) (see Section 3.8 of this progress report).

Forecast: Future work on this study will be controlled and tracked through Study 8.3.1.12.1.1, discussed in Section 3.8.1 of this progress report.

3.9 OFFSITE INSTALLATIONS AND OPERATIONS (SCP SECTION 8.3.1.13)

Changes to the Offsite Installations and Operations Program since the SCP was issued are summarized in Appendix A, Section A.1.10.

The objective of this program is to provide information required to support resolution of design and performance issues related to offsite radiological safety, including (a) evaluations of offsite accident initiators, their probabilities and potential impacts; (b) assessments of routine releases from nuclear operations; (c) assessments of the onsite impacts of nonrepository-related routine and potential accidental releases of radioactive material; and (d) collection of agricultural and cultural data to support the calculation of the dose to the public from releases at the Yucca Mountain Site.

No progress was made during the reporting period; this is an out-year activity.

Forecast: No activity is planned for FY 1997.

3.10 SURFACE CHARACTERISTICS (SCP SECTION 8.3.1.14)

Changes to the Surface Characteristics Program since the SCP was issued are summarized in Appendix A, Section A.1.11.

3.10.1 Study 8.3.1.14.2.1 - Exploration Program

The objective of this study is to conduct an exploration program for the characterization of the soil and rock conditions that will influence or be influenced by the construction of the surface facilities and the subsurface facilities. The exploration program study will consist of site reconnaissance and preliminary and detailed exploration.

Activity 8.3.1.14.2.1.1 - Site reconnaissance. The objective of this activity is to review existing site information and conduct field reconnaissance to establish a preliminary exploration program to include further topographic and geologic mapping, subsurface drilling, test pits, trenching, and geophysical methods.

The reconnaissance activities identified in the objective statement have been completed. No new activity occurred during the reporting period.

Activity 8.3.1.14.2.1.2 - Preliminary and detailed exploration. The objective of this activity is to obtain sufficient surface and subsurface data to prepare a preliminary design for the ESF surface and subsurface access facilities. Preliminary designs based on these explorations will be suitable for economic and technical feasibility reports and Project planning reports.

A report on the geoengineering characterization of the ESF main drift (Kicker et al., 1996) was completed. The data summarized in the report address the major topics of geologic setting, geologic features of engineering and construction significance, and expected ground conditions, and range of required ground support.

Forecast: No activity is planned for this study in FY 1997.

3.10.2 Study 8.3.1.14.2.2 - Laboratory Tests and Material Property Measurements

The objective of this study is to conduct laboratory tests and material property measurements on representative samples of soil and rock. These tests and measurements are intended to determine physical, mechanical, and dynamic properties. Additional tests and measurements will be conducted on soils to determine index properties and moisture-density compaction curves for potential fill material.

Activity 8.3.1.14.2.2.1 - Physical property and index laboratory tests. The objective of this activity is to measure the soil or rock weight and volume components using physical property tests.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.14.2.2.2 - Mechanical and dynamic laboratory property tests. The objective of this activity is to measure in the laboratory the static and dynamic deformation and strength characteristics of soil and rock samples obtained from the exploratory program. The results of

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this testing will be used to evaluate bearing capacity, earth pressures, shear strength parameters, slope stability, settlement and swelling potentials, and the dynamic characteristics of the soil and rock.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No additional activity is planned for FY 1997.

3.10.3 Study 8.3.1.14.2.3 - Field Tests and Characterization Measurements

The objective of this study is to conduct field tests and characterization measurements. These field tests are intended to determine the in situ physical, mechanical, and dynamic properties of the soil and rock.

Activity 8.3.1.14.2.3.1 - Physical property field tests and characterization measurements. The objectives of this activity are to classify and describe the soil and rock conditions in the field and to determine their physical properties. The results of these tests and measurements will be used to estimate the engineering characteristics of the soil and rock. In addition, these properties and measurements will aid in the grouping of soil and rock into stratigraphic units and the extrapolation of results from a restricted number of mechanical and dynamic properties tests to zones of soil and rock with similar material properties.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.14.2.3.2 - Mechanical property field tests. The objective of this activity is to measure the deformation and strength characteristics of in situ soil and rock conditions. The results of this testing will be used to design ESF surface facilities and underground openings.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.14.2.3.3 - Geophysical field measurements. The objectives of this activity are to obtain measurements of the compressional and shear wave velocities and to determine the velocity structure in the area of the ESF surface facilities and subsurface ramps and shafts. These methods may also be used to profile the alluvium-bedrock contact, to locate discontinuities or other structural features, and to determine the depth, thickness, and lateral extent of soil and rock stratigraphic units.

This activity has been completed. The compilation and analysis of geophysical data are described under Activity 8.3.1.4.1.2 (Integration of Geophysical Activities), discussed in Section 3.3.2 of this progress report.

Forecast: No activity is planned for this study in FY 1997.

3.11 THERMAL AND MECHANICAL ROCK PROPERTIES (SCP SECTION 8.3.1.15)

Changes to the Thermal and Mechanical Rock Properties Program since the SCP was issued are summarized in Appendix A, Section A.1.12.

The Site Geotechnical Report (CRWMS M&O, 1996m) synthesizes the available qualified geotechnical data required to support the evaluation of the Yucca Mountain site. The data summarized in the report have implications for engineering design and performance assessment.

The Site Geotechnical Report presents the results of the geological and geotechnical investigations that support the design and construction of the ESF. The primary purpose of the first revision of the report is to provide the results of the data collection program for the lithostratigraphic unit making up the potential repository horizon. Data for the Topopah Spring Tuff middle nonlithophysal unit were collected under several surface, laboratory, and subsurface studies. Those that are part of the Surface Characteristics Program (see Section 3.11 of this progress report) are: Study 8.3.1.14.2.1 (Exploration Program), Study 8.3.1.14.2.2 (Laboratory Tests and Material Property Measurements), Study 8.3.1.14.2.3 (Field Tests and Characterization Measurements). Those studies that are part of the Thermal and Mechanical Rock Properties Program include, Study 8.3.1.15.1.1 (Laboratory Thermal Properties), Study 8.3.1.15.1.2 (Laboratory Thermal Expansion Testing), Study 8.3.1.15.1.3 (Laboratory Determination of Mechanical Properties of Intact Rock), Study 8.3.1.15.1.4 (Laboratory Determination of the Mechanical Properties of Fractures), Study 8.3.1.15.1.5 (Excavation Investigations), Study 8.3.1.15.1.7 (In Situ Mechanical Properties), Study 8.3.1.15.1.8 (In Situ Design Verification), and Study 8.3.1.15.2.1 (Characterization of the Site Ambient Stress Conditions). Data from these studies were used (a) to generate stratigraphic cross sections along the ESF; (b) to determine intact rock properties, including estimates of porosity, density, strength, elastic modulus, thermal expansion, thermal conductivity, and heat capacity; (c) to determine fracture strength and stiffness; (d) to estimate rock mass quality; and (e) to estimate rock mass mechanical properties including strength and deformation modulus. These data were collected for some, but not all, of the lithostratigraphic units intersected by the ESF.

3.11.1 Study 8.3.1.15.1.1 - Laboratory Thermal Properties

The objective of this study is to provide laboratory characterization of thermal conductivity and heat capacity and provide data to describe the spatial variability of these parameters. To accomplish this, porosity, grain density, and the heat capacity and thermal conductivity of zero-porosity material must also be characterized.

Responses to NRC staff questions on the study plan were transmitted to the NRC (DOE, 1996h).

Activity 8.3.1.15.1.1.1 - Density and porosity characterization. The objective of this activity is to obtain data on density and porosity and to evaluate the spatial variability thereof.

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Data will contribute to determining in situ thermal properties (porosity and grain density), vertical in situ stress (bulk density), and radiation-shielding properties (bulk density).

No progress was made during the reporting period; this was an out-year activity.

Density and porosity measurements for test specimens from the single heater test area of the Thermal Testing Facility were conducted and are reported under Study 8.3.4.2.4.4 (see Section 5.2.5 of this progress report).

Activity 8.3.1.15.1.1.2 - Volumetric heat capacity characterization. The objective of this activity is to obtain data for volumetric heat capacity and to evaluate the spatial variability thereof. The data will be used in calculations of the thermal response to the presence of heat-producing waste in unit TSw2.

No testing was conducted during the reporting period; testing was an unfunded activity. Heat capacity data for 10 test specimens from boreholes UE-25 NRG#4 and UE-25 NRG#5 were resubmitted to the Reference Information Base and incorporated into the Site Geotechnical Report (CRWMS M&O, 1996m). These data are also included in Brodsky et al. (in prep.), which was revised and resubmitted.

Activity 8.3.1.15.1.1.3 - Thermal conductivity characterization. The objective of this activity is to obtain data for thermal conductivity and to evaluate the spatial variability thereof. The data will be used on calculations of the thermal response to the presence of heat-producing waste in unit TSw2.

Experimental data on samples from boreholes UE-25 NRG#4, UE-25 NRG#5, USW NRG-6, and USW NRG-7/7a were incorporated into the Site Geotechnical Report (CRWMS M&O, 1996m). These data are also included in Brodsky et al. (in prep.), which was revised and resubmitted. All supporting scientific notebooks were submitted to the Participant Data Archive. Thermal conductivity measurements for test specimens from the single heater test area of the Thermal Testing Facility proceeded and are reported under Study 8.3.4.2.4.4 (see Section 5.2.5 of this progress report).

Forecast: The data from this study will be used in calculations of thermal stress and deformation associated with the temperature field produced by the presence of heat-producing waste in unit TSw2 (lithostratigraphic units Tptpmn, Tptpll, and Tptpln) (see Geologic/Lithologic Stratigraphy, MO 9510R1B00002.004). Samples from the ESF will be tested to determine the lateral variability and anisotropy of thermal conductivity and thermal expansion properties.

3.11.2 Study 8.3.1.15.1.2 - Laboratory Thermal Expansion Testing

The objective of this study is to provide laboratory characterization of thermal expansion behavior and the spatial variability. This information will be used to establish the testing frequency at the main test level in the ESF.

Responses to NRC staff questions on the study plan were transmitted to the NRC (DOE, 1996h).

Experimental data on samples from boreholes UE-25 NRG#4, UE-25 NRG#5, USW NRG-6, and USW NRG-7/7a were incorporated into the Site Geotechnical Report (CRWMS M&O, 1996m). These data are also included in Brodsky et al. (in prep.), which was revised and resubmitted. All supporting scientific notebooks were submitted to the Participant Data Archive. Martin et al. (in prep.[b]) was revised and resubmitted. Thermal expansion measurements for test specimens from the Single Heater Test Area of the Thermal Testing Facility were conducted and are reported under SCP Study 8.3.4.2.4.4 (see Section 5.2.5 of this progress report).

Activity 8.3.1.15.1.2.1 - Thermal expansion characterization. The objective of this activity is to obtain data for thermal-expansion behavior and to evaluate the spatial variability thereof. The data will be used in calculations of thermal stress and deformation associated with the temperature field produced by the presence of heat-producing waste in unit TSw2.

This activity has been incorporated into Study 8.3.1.15.1.1, discussed in Section 3.11.1 of this progress report.

Forecast: The laboratory test equipment for the measurement of thermal conductivity and thermal expansion will be relocated from the contractor's offices to Sandia National Laboratories in Albuquerque, New Mexico. Planned test activities include characterizing the main drift of the ESF. Spatial variability and the effects of anisotropy will be examined. Work related to thermal expansion testing will be reported under Study 8.3.1.15.1.1, Laboratory Thermal Properties.

3.11.3 Study 8.3.1.15.1.3 - Laboratory Determination of Mechanical Properties of Intact Rock

The objective of this study is to provide laboratory characterization of the mechanical properties of intact rock, including the spatial variability and the effects of changes in environmental conditions.

Activity 8.3.1.15.1.3.1 - Compressive mechanical properties of intact rock at baseline experiment conditions. The objective of this activity is to obtain data for the compressive mechanical properties of intact rock and the spatial variability thereof for baseline experiment conditions. These data will be used in mechanical and thermomechanical calculations of stresses and deformations induced by the presence of underground openings in unit TSw2 and overlying units and by the presence of heat-producing waste in unit TSw2.

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No funding was provided in FY 1996 to generate additional data. A report (Boyd et al., in prep.) on the mechanical properties of samples from boreholes USW NRG-6 and USW NRG-7/7a was revised and resubmitted to DOE/YMSCO. Data on the mechanical properties of intact rock were incorporated into the Site Geotechnical Report (CRWMS M&O, 1996m). Uniaxial compressive strength and elastic moduli measurements for test specimens from the single heater test area of the Thermal Testing Facility were conducted and are reported under SCP Study 8.3.4.2.4.4 (see Section 5.2.5 of this progress report)..

Activity 8.3.1.15.1.3.2 - Effects of variable environmental conditions on mechanical properties. The objective of this activity is to evaluate the effects of varying sample size, strain rate, temperature, confining pressure, lithophysal content, saturation state, and anisotropy on compressive mechanical properties. Data will be used in mechanical and thermomechanical calculations of stresses and deformations induced by the presence of heat-producing waste in unit TSw2 (lithostratigraphic units Tptpmn, Tptpll, and Tptpln) (see Figure 3-5).

A report (Martin et al., in prep.[a]), on the creep characteristics of welded tuff specimens from borehole USW NRG-7/7a, was revised and resubmitted. All scientific notebooks associated with this activity are being reviewed before the data is submitted to the GEographic Nodal Information Study and Evaluation System (GENISES). These data were incorporated into the Site Geotechnical Report (CRWMS M&O, 1996m).

Forecast: The report (Martin et al., in prep.[a]) will be published, and all scientific notebooks will be submitted to the Records Processing Center. The main drift of the ESF will be characterized and the spatial variability and effects of anisotropy and temperature will be examined.

3.11.4 Study 8.3.1.15.1.4 - Laboratory Determination of the Mechanical Properties of Fractures

The objective of this study is to provide laboratory characterization of the mechanical properties of fractures, including the spatial variability and the effects of changes in environmental conditions.

Activity 8.3.1.15.1.4.1 - Mechanical properties of fractures at baseline experiment conditions. The objective of this activity is to obtain data for the mechanical properties of fractures, and the spatial variability thereof, for baseline experiment conditions. The data will be used in mechanical and thermomechanical calculations of the stresses and deformations induced by the presence of underground openings in unit TSw2 and overlying units and by the presence of heat-producing waste in unit TSw2.

No progress was made during the reporting period; this was an unfunded activity.

Activity 8.3.1.15.1.4.2 - Effects of variable environmental conditions on mechanical properties of fractures. The objective of this activity is to evaluate the effects of varying normal

stress, displacement rate, temperature, sample size, fracture roughness, and saturation state on the mechanical properties of artificial and natural fractures. The data will be used in mechanical and thermomechanical calculations of stresses and deformations induced by the presence of underground openings in unit TSw2 and overlying units and by the presence of heat-producing waste in unit TSw2.

A testing and analysis program was completed to determine fracture properties at elevated temperature (175°C). Eight specimens were tested in rotary shear at 175°C and at normal stresses of 2.5, 5, 10, and 15 MPa. Results from these tests were compared with the results of similar tests obtained previously at room temperature. The elevated temperature data show slightly higher cohesions and coefficients of friction than the room temperature data; however, these differences are small (one standard deviation or less). The elevated temperature data show less scatter than the room temperature data. This may be an artifact of comparing small data sets, or, it may be the result of other factors (e.g., more uniform moisture contents due to drying at 175°C). The data were compiled and submitted to the Technical Data Base. All scientific notebooks pertaining to this work have been submitted and are under review. Scientific notebooks pertaining to previous work on samples from boreholes UE-25 NRG#4, USW NRG-6, NRG-7/7a, USW SD-9, and USW SD-12 were completed, reviewed, and submitted to the GENISES.

Data obtained during FY 1995 were compiled and resubmitted to the Technical Data Base. These submittals included data on fracture properties of samples from borehole USW SD-9 and on fracture properties of borehole USW SD-12.

Forecast: Tests will be performed on samples from the ESF to assess the lateral variability of mechanical properties of fractures at baseline conditions.

3.11.5 Study 8.3.1.15.1.5 - Excavation Investigations

The objective of this study is to obtain site-specific information concerning the behavior of underground excavations in the proposed repository horizon and overlying units. Most of the data will be used for testing of computer codes that will be used to predict mechanical behavior of the rock mass. In addition, some of the information will directly demonstrate performance of repository-scale openings.

Activity 8.3.1.15.1.5.1 - Access convergence experiment. The objective of this activity is to monitor rock-mass deformation around accesses as they are constructed. The intent in the SCP (DOE, 1988) was to measure rock stress changes and deformation of the rock mass as a shaft was progressively constructed to the repository horizon. Since the SCP, changes in the ESF design and testing strategy have lead to a new ESF design where shafts are replaced by a single tunnel. This change made most of this activity unnecessary or a duplication of the efforts being pursued under Study 8.3.1.15.1.8 (Section 3.11.8 of this progress report).

No progress was made during the reporting period; this was an unfunded activity.

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Activity 8.3.1.15.1.5.2 - Demonstration breakout room. The objective is to demonstrate constructability and stability of underground rooms with cross-sectional dimensions equivalent to those of a repository in both lithophysae-rich and lithophysae-poor material.

This test was based on data needs related to the ESF design described in the SCP (DOE, 1988) and has been deferred because access to the ESF is by ramps rather than shafts. Test information related to this activity is being collected under Study 8.3.1.15.1.8 (see Section 3.11.8 of this progress report).

Activity 8.3.1.15.1.5.3 - Sequential drift mining. The objectives of this activity are to obtain data on the deformation response of drifts with cross-sectional dimensions equivalent to those of a repository in welded tuff, to use the data in model evaluation activities, and to demonstrate constructability and stability of repository-sized drifts in lithophysae-poor material. Data will contribute to validating computer models to be used to calculate mechanical responses, as well as empirical evaluations related to nonradiological health and safety.

Detailed planning for this test was completed in FY 1996. The test plan is described in the Thermal Test Design and Layout Report (CRWMS M&O, 1996n). The current plan involves installing multipoint-displacement measuring instrumentation from an access drift to near the location where the heated drift test drift will be excavated. This instrumentation will be in place before the heated drift is excavated and is intended to measure the near-field rock response as the drift is excavated. The instrumentation installed for this test will remain in place and also be used for the drift-scale thermal test to measure rock response to repository emplacement room heating.

Forecast: The test instrumentation is scheduled to be installed starting in October 1996. The test will be conducted in conjunction with construction of the Thermal Testing Facility.

3.11.6 Study 8.3.1.15.1.6 - In Situ Thermomechanical Properties

The objective of this study is to obtain data on in situ thermal and thermomechanical properties for units TSw1 and TSw2. Properties to be obtained include heat capacity, thermal conductivity, and thermal expansion. Additional heater experiments will be conducted to characterize the waste container environment.

Study Plan 8.3.1.15.1.6 was completed and accepted by YMSCO. Planning and design for the ESF single heater test and the drift-scale test began in early FY 1996. Progress on design and planning has been documented in the Thermal Test Design and Layout Report (CRWMS M&O, 1996n).

Activity 8.3.1.15.1.6.1 - Heater experiment in unit TSw1. The objectives of this activity are to estimate the in situ thermomechanical properties of lithophysae-rich tuff (unit TSw1) and to evaluate the thermal and mechanical response of this tuff unit to elevated temperatures.

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A single heater test in TSw1 was proposed as an alternative test if the ESF construction was delayed (DOE, 1995j). Because of rapid progress in ESF construction, this test is being deferred in favor of testing in the TSw2.

Activity 8.3.1.15.1.6.2 - Canister-scale heater experiment. The objective of this activity is to obtain thermal and thermomechanical rock-mass measurements of the effects of thermal inputs on a representative scale in lithophysae-poor tuff (unit TSw2). The data will be used to evaluate thermal and thermomechanical properties of the rock mass and to evaluate the thermal and thermomechanical models.

Because of the consolidation of the thermal testing program, this test was combined with some elements of other tests into the single heater test. A detailed design of the single heater test has been completed and documented in the Thermal Test Design and Layout Report (CRWMS M&O, 1996n). The test planning and field work packages for conducting the test were developed and issued. Initial excavation of the Thermal Testing Alcove for the single heater test site and drilling of instrument boreholes began in April and was completed in May 1996.

Installation of instrumentation, the heater assembly, and the data acquisition system were completed in August. After a management assessment of the design and installation process, and completion of the installation checks, the heater was turned on and ramped up to a constant 4.0 kW power level. Early data from the instrumentation indicate that most sensors appeared to be operating properly. Temperatures recorded on the heater package surface and in the surrounding rock were within bounds established by pre-test predictions. However, the geochemical sensors have not operated correctly since installation.

As part of the characterization of the Thermal Testing Alcove, samples from instrument core holes were removed and tested in the laboratory. Thermal conductivity, thermal expansion, uniaxial compressive strength, Young's Modulus, and Poisson's Ratio were measured. These parameters, along with measured air permeability, saturation levels, rock quality assessments, and other characterization data were documented in the Thermal Testing Alcove Characterization Report (CRWMS M&O, 1996o).

Additional analyses were completed using site specific data to add to the basis of pre-test analyses. Thermal-hydrological and thermal-mechanical analyses were completed and final documentation is being prepared.

Activity 8.3.1.15.1.6.3 - Yucca Mountain heated block. The objective of this activity is to estimate in situ mechanical and thermomechanical properties of unit TSw2 and to test thermomechanical models.

The data needs and objectives related to this test have been combined into the Thermal Testing Facility tests, under Activities 8.3.1.15.1.6.2 and 8.3.1.15.1.6.5. (Note: Status of Thermal Testing Facility design and construction are described in Sections 7.1.2 and 7.3.3, respectively, of this progress report.)

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Activity 8.3.1.15.1.6.4 - Thermal stress measurements. The objective of this activity is to monitor thermally induced stress in jointed welded tuffs in an accelerated test.

The data needs and objectives related to this test have been combined into the Thermal Testing Facility now being designed under Activities 8.3.1.15.1.6.2 and 8.3.1.15.1.6.5. (Note: Status of Thermal Testing Facility design and construction are described in Sections 7.1.2 and 7.3.3, respectively, of this progress report.)

Activity 8.3.1.15.1.6.5 - Heated room experiment. The objectives of this activity are (a) to evaluate the thermomechanical response of welded tuff around repository openings to expected repository conditions during both construction and operation; (b) to develop a data base for evaluating thermal and thermomechanical design analyses and methods applicable for repository considerations; and (c) to use actual site data in predicting drift response and support/rock interactions during construction, operation, retrievability, and postclosure.

This test has been combined into the drift-scale test portion of the Thermal Testing Facility. Thermal-mechanical-hydrological-chemical coupling will be explored in the drift-scale test. A preliminary test configuration has been developed and documented in the Thermal Test Design and Layout Report (CRWMS M&O, 1996n). Test facility requirements have been given to the ESF design organization to complete the design of the Thermal Testing Facility. The test consists of a single heated drift 5 m in diameter, with in-drift heater canisters to simulate waste packages. To accelerate the test, "wing" heaters are emplaced in the ribs of the drift. The heated portion of the drift will be approximately 55 m long with a 35 m long thermal-hydrology section and an approximately 20 m section where different engineering ground support methods will be tested and observations of the coupled process will be made. The heat from the wing heaters will cause the heated profile to simulate a drift within a multidrift heated repository. The location and type of instrumentation to be used in the test have been identified in the test plan and are currently being refined in the final design phase. The sequential drift mining test, under Study 8.3.1.15.1.5 (Section 3.11.5 of this progress report), is being conducted as part of the construction of the heated drift test.

Forecast: The single heater test will continue, and data will be analyzed and compared with pre-test modeling results. Additional modeling will be performed using site-specific data for these comparisons. A design for the drift-scale test will be completed and documented. The instrument boreholes will be drilled and instruments installed from the access drift for the sequential drift mining test part of the heated drift test.

3.11.7 Study 8.3.1.15.1.7 - In Situ Mechanical Properties

The objective of this study is to obtain in situ measurements of the mechanical properties of the rock mass for unit TSw2.

Study Plan 8.3.1.15.1.7, In Situ Mechanical Properties, was completed and accepted by YMSCO.

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Activity 8.3.1.15.1.7.1 - Plate loading tests. The objective of this activity is to measure the deformation modulus of the rock mass and to evaluate the zone of increased fracturing adjacent to underground openings. A plate loading test will be conducted as part of the heated drift test. This will allow the measurement of rock-mass modulus under both ambient and heated conditions. The planning for this test is taking place as part of the consolidated thermal test.

The consolidated thermal test consists of two tests: the single heater test (Activity 8.3.1.15.1.6.2), and the drift scale test (Activity 8.3.1.15.1.6.5) as described in the In-Situ Thermal Testing Program Strategy (DOE, 1995j). A preliminary design of the plate loading test associated with the ESF thermal test was developed and documented in the Thermal Test Design and Layout Report (CRWMS M&O, 1996n).

Activity 8.3.1.15.1.7.2 - Rock-mass strength experiment. The objective of this activity is to evaluate the mechanical behavior of the rock mass or its components by using experiments to obtain information related to the mechanical strength of single joints and to multiply jointed volumes of rock.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: The plate loading test design will be finalized. Partial installation of the test equipment will be completed in late FY 1997.

3.11.8 Study 8.3.1.15.1.8 - In Situ Design Verification

The objectives of this study are (a) to investigate the effects of the spatial variability of the rock on drift stability, mining activities, and ground supports; (b) to evaluate techniques for underground excavation and ground support, for selecting ground supports to be used in different rock types, and for monitoring drift stability; (c) to quantify the emanation of radon into repository drifts and observe its dispersion with airflow; and (d) to measure parameters needed to design repository ventilation systems.

Geotechnical design verification activities have been conducted in the ESF to provide data that can be used to confirm adequacy of design, construction, and long-term performance since the beginning of ESF construction. The data from these activities will also be used to support repository design and to validate the ESF design.

Activity 8.3.1.15.1.8.1 - Evaluation of mining methods. The objective of this activity is to develop a recommendation for mining in the repository by monitoring and evaluating mining activities in the ESF and by conducting mining investigations.

Evaluations of rock mass quality have been keeping pace with ESF excavation. These evaluations were needed for correlation with other studies and to substantiate ground support decisions made by the ESF constructor. Preliminary data were submitted daily and the reviewed data were submitted monthly to the records center.

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Construction monitoring included measurement of the near-field and far-field peak particle velocities caused by drill and blast excavation methods. Blast monitoring was performed during the construction of the Thermal Testing Facility access/observation drift and the Northern Ghost Dance Fault Alcove. Peak particle velocities were measured, and a scaled distance model was developed. Measured velocities have shown considerable variability, and no work to determine the distribution of the particle velocities has been done. Peak particle velocities serve as empirical indicators of the extent of blast damage in the surrounding rock. Preliminary data were submitted on a daily basis, and the reviewed data were submitted bimonthly to the Records Processing Center.

Activity 8.3.1.15.1.8.2 - Monitoring of ground-support systems. The objective of this activity is to develop recommendations for a ground-support methodology to be used in repository drifts, based on evaluations of the ground-support methodology being used in the ESF and experimentation with other ground-support configurations. Support systems will be recommended, as will methods of selecting appropriate supports for the ground conditions encountered.

Project scientists continued to monitor installed geotechnical instruments and installed new geotechnical instruments closely following the ESF excavation. The geotechnical instrumentation included convergence pins, multipoint and single-point borehole extensometers, and strain gauges on steel sets installed as part of the ground support. Strain gauges were installed on selected steel sets either before or after installation. For pre-installed strain gauges, measurements of installation loads were made before, during, and after installation. Readings from these instruments have identified no significant concerns regarding the integrity of ground support. Reviewed data were submitted quarterly to the Records Processing Center, with an annual summary report submitted at the end of FY 1996.

Activity 8.3.1.15.1.8.3 - Monitoring drift stability. The objectives of this activity are (a) to provide confidence in predictions of usability of the repository underground facilities for their 100-year operational life, (b) to contribute to evaluations of the effectiveness of mining methods and ground supports, (c) to calibrate and refine criteria for determining stability of the openings, and (d) to develop techniques for monitoring stability of the repository drifts.

Project scientists continued to monitor installed geotechnical instruments and installed new geotechnical instruments closely following the ESF excavation. The geotechnical instrumentation included multipoint and single-point extensometers and cross-drift convergence pins. Readings from these instruments have identified no significant concerns related to tunnel stability. Reviewed data were submitted quarterly to the Records Processing Center, with an annual summary report submitted at the end of the fiscal year.

Activity 8.3.1.15.1.8.4 - Air quality and ventilation experiment. The objectives of this activity are to measure the rate of radon emanation from the repository host rock and to evaluate parameters and variables needed as input to or for testing of the models to be used to design the ventilation systems in the repository underground facility.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Monitoring of instrumentation in the ESF south ramp will continue until the tunnel boring machine emerges at the south portal. Monitoring of installed instrumentation will continue on a quarterly basis after the tunnel boring machine emerges.

3.11.9 Study 8.3.1.15.2.1 - Characterization of the Site Ambient Stress Conditions

The objective of this study is to characterize the ambient (pre-repository) state of stress of the Yucca Mountain host rock and surrounding units for use as initial conditions for geomechanical models used in the design and performance assessment of the repository underground facilities.

Activity 8.3.1.15.2.1.1 - Anelastic strain recovery experiments in core holes. The objective of these experiments using samples from core holes is to determine the horizontal stresses at Yucca Mountain and especially the spatial variability of these stresses. In situ stress data will contribute to the definition of initial and boundary conditions for mechanical and thermomechanical analyses.

This activity was developed to support design and operation of the shaft configuration of the ESF and potential repository. Abandonment of the shaft configuration has eliminated the need for this activity. No activity occurred during the reporting period.

Activity 8.3.1.15.2.1.2 - Overcore stress experiments in the Exploratory Studies Facility. The objectives of this activity are to determine the in situ state of stress above, within, and below the repository host rock in that portion of the repository block penetrated by the ESF, and to evaluate the extent to which the ambient stress conditions are redistributed adjacent to excavations. In situ stress data will contribute to the definition of initial and boundary conditions for mechanical and thermomechanical analyses.

The scope of work for this activity has been transferred to Study 8.3.1.15.1.8 (see Section 3.11.8 of this progress report).

Forecast: No further work is planned for this study.

3.11.10 Study 8.3.1.15.2.2 - Characterization of the Site Ambient Thermal Conditions

The objective of this study is to evaluate available thermal data to determine the ambient (pre-repository) temperature and thermal conductivity of the Yucca Mountain host rock and surrounding units for use as initial conditions for thermomechanical models used in the design and performance assessment of the repository underground facilities.

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Activity 8.3.1.15.2.2.1 - Surface-based evaluation of ambient thermal conditions. The objectives of this activity are to measure the spatial variation of temperature with depth in existing wells; provide baseline temperatures within the repository host rock and surrounding units; measure thermal conductivity (near 25°C) of core samples to check on independent thermal property determinations at various temperatures; and determine heat flow at Yucca Mountain.

Data collection for this activity has been transferred to Study 8.3.1.8.5.2, and pertinent activities are reported under that study (see Section 3.6.9 of this progress report).

Forecast: No additional activity is planned for this study.

3.11.11 Related International Thermal and Mechanical Rock Properties Work

No progress was made during the reporting period. As of November 8, 1995, the subsidiary agreements under which the cooperative work had been conducted were terminated, and all international collaboration was discontinued.

The OCRWM had bilateral and technical cooperative agreements with Canada (Atomic Energy of Canada Limited [AECL]), Switzerland (Swiss National Cooperative for the Storage of Radioactive Waste [Nagra]), and Sweden (Swedish Nuclear Fuel and Waste Management Company [SKB]) and has participated in activities of international organizations such as the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the Commission of European Communities (CEC).

Forecast: No work is planned under the international program.

3.12 PRECLOSURE HYDROLOGY (SCP SECTION 8.3.1.16)

Changes to the Preclosure Hydrology Program since the SCP was issued are summarized in Appendix A, Section A.1.13.

3.12.1 Study 8.3.1.16.1.1 - Characterization of Flood Potential of the Yucca Mountain Site

The objective of this study is to evaluate the potential for flooding in the many small, dry, desert washes that drain Yucca Mountain. This evaluation will be used for designing the surface facilities for the proposed repository. Proper design for flood potential is necessary to ensure the safety of workers and surface facilities.

No activities have been funded under this study since FY 1993. Flood potential for the site has been described in the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k).

Forecast: No activities are planned for this study.

3.12.2 Study 8.3.1.16.2.1 - Location of Adequate Water Supply for Construction, Operation, Closure, and Decommissioning of a Mined Geologic Disposal System at Yucca Mountain, Nevada

The objective of this study is to identify water supply sources for a potential repository. Four activities were identified in the SCP: (1) assess the cost, feasibility, and adequacy of using wells UE-25 J#12 and UE-25 J#13 as an alternative water supply; (2) identify a primary water source; (3) identify another alternative water source (other than wells UE-25 J#12 and UE-25 J#13); and (4) identify and evaluate the potential effects of repository-related withdrawals on the ground-water flow system.

This study uses data from other studies; therefore no study plan will be developed. No activities have been funded under this study since FY 1991. Water resource data were reviewed in the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k).

Forecast: No activities are planned for this study.

3.12.3 Study 8.3.1.16.3.1 - Determination of the Preclosure Hydrologic Conditions of the Unsaturated Zone at Yucca Mountain, Nevada

The objective of this study is to compile the data collected under Geohydrology Investigation 8.3.1.2.2 for input to Design Issue 4.4.

The purpose of this study was to describe ground-water conditions within and along the potential repository block. Work originally planned for this study has been incorporated into and performed under Study 8.3.1.2.2.9, discussed in Section 3.1.13 of this progress report.

Forecast: No further work is planned under this study.

3.13 PRECLOSURE TECTONICS (SCP SECTION 8.3.1.17)

Changes to the Preclosure Tectonics Program since the SCP was issued are summarized in Appendix A, Section A.1.14.

3.13.1 Study 8.3.1.17.1.1 - Potential for Ash Fall at the Site

The objective of this study is to provide required information on volcanic activity that could affect repository design performance.

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Because of the study plan work scope consolidation, this study was combined with Study 8.3.1.17.3.6 (see Section 3.13.8 of this progress report). Therefore, no study plan will be developed. All these activities rely on data from other studies, or on available data. The work identified in this section has been completed and was documented in Perry and Crowe (1987).

The response to the NRC comment on Progress Report #11 (NRC, 1995c) concerning the potential for ash fall at the site was transmitted to the NRC (DOE, 1996k).

Activity 8.3.1.17.1.1.1 - Survey literature regarding Quaternary silicic volcanic centers in the western Great Basin. The objective of this activity is to compile information on Quaternary silicic volcanism in the western Great Basin, the reoccurrence of which might produce an ash fall at the site.

This activity has been completed.

Activity 8.3.1.17.1.1.2 - Assess potential ash-fall thickness at the site. The objective of this activity is to produce an approximate probability-versus-thickness function for potential ash falls at the site and to estimate a particular ash-fall thickness that has less than one chance in ten of occurring in 100 years. These hazard estimates will be considered in the design of filters in the mining and surface-facility ventilation systems.

This activity has been completed.

Forecast: No additional work is planned for this study.

3.13.2 Study 8.3.1.17.2.1 - Faulting Potential at the Repository

The objective of this study is to provide required information on fault displacement that could affect repository design or performance.

No study plan was developed. The work scope for this study has been combined with that of Study 8.3.1.17.3.6 (see Section 3.13.8 of this progress report).

Forecast: No further work is planned under this study.

3.13.3 Study 8.3.1.17.3.1 - Relevant Earthquake Sources

The objective of this study is to identify and characterize those earthquake sources relevant to seismic hazard analysis of the site (i.e., those sources that could cause significant surface fault displacement or ground shaking at the site).

Study Plan 8.3.1.17.3.1, Relevant Earthquake Sources, Rev. 1, was submitted to the NRC (DOE, 1996m). Revision 1 incorporates DOE's current approach to seismic hazard assessment

as described in the topical report: Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain (DOE, 1994b). The revised study plan also addresses Site Characterization Analysis comments 48 and 66, but closure of these open items will require the completion of the probabilistic seismic hazard analysis project scheduled for FY 1997. The study plan revision also considered NRC guidance on fault identification (McConnell et al., 1992). The revision drops the concept of a 10,000-year cumulative slip earthquake, describes a method to evaluate the maximum magnitude for identified seismic sources using estimates of the physical dimension of potential future fault rupture, and describes the use of probabilistic seismic hazard analysis to assess seismic hazards at Yucca Mountain, Nevada.

Activity 8.3.1.17.3.1.1 - Identify relevant earthquake sources. The objective of this activity is to identify earthquake sources that could generate significant surface fault displacements or severe ground motions at the site.

Faults considered significant for assessing ground motion and fault displacement hazards with respect to the potential repository are discussed in a chapter on relevant earthquake sources (Pezzopane, 1996) that was prepared for inclusion in the synthesis report on the seismotectonic framework of Yucca Mountain (see Study 8.3.1.17.3.6, Section 3.13.8 of this progress report) (Whitney, 1996). Faults were identified using several sources of data, including (1) compilations of regional and local faults by Piety (1996) and Simonds et al. (1995b), respectively; (2) recent field studies of selected faults in areas adjacent to Yucca Mountain (e.g., Anderson et al., 1995a and b); and (c) results of trenching activities and paleoseismic studies of faults in the immediate vicinity of the potential repository (see Study 8.3.1.17.4.6, Section 3.13.14 in this progress report). During the investigations, 100 individual faults, or combinations of closely related faults, were selected for further examination as to the nature of the evidence (documented or questionable) for Quaternary activity and for determining whether maximum magnitude earthquakes on these faults could produce peak ground accelerations at the potential repository that equal or exceed 10 percent of gravity at the 84th percentile level of confidence.

The report on relevant earthquake sources (Pezzopane, 1996) includes a table that lists fault data and ground motion estimates for the known and suspected Quaternary faults in the Yucca Mountain region (generally within 100 km of the potential repository site). In addition to information on minimum distances from the site and maximum fault lengths, the table includes maximum moment magnitudes and average peak accelerations with respect to the potential repository as calculated from methods discussed in an accompanying text. These data, supplemented by summary descriptions of faults given in a companion chapter of the seismotectonic framework synthesis report (Whitney, 1996) (see Study 8.3.1.17.4.3, Section 3.13.11 of this progress report), indicated that 67 individual faults, or fault combinations, are important to seismic hazard assessments because of their calculated ground motions. Of these, 36 are classed as "relevant" because of documented Quaternary activity, and the remainder are classed as "potentially relevant" because clear evidence of Quaternary movement has not yet been demonstrated. All 67 faults occur within 70 km of the potential repository site.

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Activity 8.3.1.17.3.1.2 - Characterize relevant earthquake sources. The objective of this activity is to characterize each relevant earthquake source identified in the previous activity by providing a spatial description (including an expected depth or depth range), an assessment of activity, evaluations of maximum earthquake magnitude, the size and location of expected coseismic displacements (for sources in or near the controlled area), and the recurrence rate for earthquakes associated with the source. The source characterization includes an evaluation of variability in and dependency of input parameters.

Data pertaining to the characteristics of the relevant earthquake sources identified in the previous activity (8.3.1.17.3.1.1) are contained in several parts of the seismotectonic framework synthesis report (Whitney, 1996). The synthesis report includes chapters on relevant earthquake sources (Pezzopane, 1996), and on earthquake recurrence and preliminary paleoearthquake magnitudes for Quaternary faults near Yucca Mountain (Pezzopane et al., 1996), as well as a summary of issues and information relative to fault displacement hazards (Pezzopane and Dawson, 1996). The combined text descriptions, tables, and graphic materials provide information on all the identified relevant earthquake sources. The principal focus is on those features closest to Yucca Mountain that are estimated to have the largest effect on the potential repository in terms of maximum magnitude earthquakes and peak accelerations of ground motion.

As described for Activity 8.3.1.17.3.1.1, the chapter on relevant earthquake sources (Pezzopane, 1996) contains a table that lists, for each source, its minimum distance from the potential site and its maximum length. These are important parameters for empirically determining maximum magnitudes and levels of ground motion. The chapter on models of earthquake recurrence and preliminary paleoearthquake magnitudes at Yucca Mountain (Pezzopane et al., 1996) summarizes data on faults nearest to the potential repository, including (a) type, strike, dip, and length of fault and (b) all available information on Quaternary activity, such as number of paleoseismic events, amounts of displacement, and ages of movement. The chapter on fault displacement hazards (Pezzopane and Dawson, 1996) provides a compilation and an analysis of the geological effects associated with predominantly transtensional earthquakes located within the extensional cordillera of the western United States; emphasis is on the application of these data to hazard assessments at Yucca Mountain (Study 8.3.1.17.3.6, Section 3.13.8 of this progress report). Focusing on the large-magnitude, surface-faulting earthquakes of the region, the study examines the patterns, amounts, and characteristics of surface ruptures, and develops relations between earthquake source properties, such as magnitude, fault dip, and focal length, and the associated rupture patterns, such as the rupture zone lengths, widths, and displacements, distributed rupture lengths and displacements, splaying or branching ruptures, and fault segmentation.

Forecast: Project staff will help plan and support the probabilistic seismic hazard analysis.

3.13.4 Study 8.3.1.17.3.2 - Underground Nuclear Explosion Sources

The objective of this study is to characterize the potential future underground nuclear explosions at the Nevada Test Site that would result in the most severe motions at the repository site.

No study plan will be developed because the activities will use available data.

Forecast: No work is planned for this study. The nuclear test-ban treaty recently signed by the President precludes underground testing for the foreseeable future.

3.13.5 Study 8.3.1.17.3.3 - Ground Motion From Regional Earthquakes and Underground Nuclear Explosions

The objective of this study is to select or develop ground-motion models that are appropriate for estimating ground motion at the site from earthquakes and underground nuclear explosions. These models will be used to determine the relevancy of seismic sources to a deterministic seismic hazard analysis, identify controlling seismic events, constrain simulated ground motions from controlling seismic events, and estimate the probabilities of exceeding given ground-motion levels at the site.

Activity 8.3.1.17.3.3.1 - Select or develop empirical models for earthquake ground motions. The objective of this activity is to select or develop empirical ground-motion models that are appropriate for estimating earthquake ground motion at the site. The models will predict ground motion as a function of earthquake magnitude and distance between the earthquake source and the site.

A chapter on the estimation of vibratory ground motion at Yucca Mountain (Abrahamson and Becker, 1996) for the seismotectonic framework synthesis report (Whitney, 1996) was developed that describes an empirical analysis of ground motion data recorded exclusively in extensional tectonic regimes worldwide. Ideally, empirical attenuation relations for Yucca Mountain should be developed from ground motion recordings of Basin and Range earthquakes; unfortunately, there are not sufficient data to constrain such a model, and global data sets are required. The study, conducted by Spudich et al. (1996), indicates that most of the empirical models developed from recordings of primarily strike-slip and reverse faulting earthquakes in western United States predict relatively higher ground motion levels than are seen from the extensional regime data. The Spudich et al. (1996) empirical model predicts lower ground motions than the western United States models at all periods except for long periods for $M > 5$ events. At greater source-to-site distances (regional earthquakes), the model provides ground motions that are about 30 to 40 percent lower than the average of the western United States models, and the standard deviation is much larger than the average of the western United States attenuation relations. The Spudich et al. (1996) model does not distinguish between strike-slip and normal faulting events in extensional regimes, and the residuals show a magnitude dependence that may correlate with the style of faulting.

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Numerical models of the seismic source path, and site effects can be used to generate synthetic ground motions for scenario earthquakes at and near Yucca Mountain. The scenario earthquake models produce larger ground motions than the western United States empirical models would predict, which are larger still than the values derived from the Spudich et al. (1996) model. The differences of the three estimates are largest at high frequencies. The Spudich et al. (1996) relation, however, does not explicitly include the effects of the low kappa (spectral decay parameter for near-surface attenuation) observed at the Yucca Mountain site, probably a result of the highly fractured tuffs that makeup the shallow crust. The average kappa of the two Yucca Mountain tuff sites (0.018 second) is lower than that of typical California soft-rock (0.04); therefore, at low levels of shaking the tuffs have less damping than for California soft-rock conditions. Assuming all other parameters are the same, larger high-frequency ground motions will occur on the Yucca Mountain tuffs (lower kappa) as compared with California soft-rock. These results are limited by the available data set, which is deficient in recordings from large magnitude events ($M > 6.5$).

Forecast: Project staff will help in planning and supporting the probabilistic seismic hazard analysis.

3.13.6 Study 8.3.1.17.3.4 - Effects of Local Site Geology on Surface and Subsurface Motions

The objective of this study is to document systematic effects on surface and subsurface ground motions resulting from the local site geology.

Activity 8.3.1.17.3.4.1 - Determine site effects from ground-motion recordings. The objective of this activity is to determine, from ground-motion recordings, the systematic effects of local site geology on surface and subsurface motions and to identify any significant site-wide bias in ground-motion levels, as compared with average levels for the southern Great Basin.

The chapter on vibratory ground motion (Abrahamson and Becker, 1996) (the development of which is discussed previously in Activity 8.3.1.17.3.3.1) also summarizes the results obtained from site response studies at three levels of detail. These levels are (1) regional attenuation studies, (2) limited velocity profiles of the uppermost several hundred meters at and near the site, and (3) laboratory measurements of the dynamic response of volcanic tuffs.

Broadband digital recordings of several of the largest aftershocks of the 1992 Little Skull Mountain earthquake ($M_L=5.6$) were used to derive kappa as a function of two terms, a distance- (or path-) dependent term and a site-dependent term. The source spectrum is assumed to follow a Brune pulse ground motion model, omega-squared displacement spectrum fall off, and $1/r$ geometric spreading. All other differences between the source and site spectra, including all path and site effects, are mapped into kappa. Results indicate that site-dependent kappa varies from 0.005 second at a station on Paleozoic rock to 0.03 second for a station on soil over Tertiary rock. On the Yucca Mountain crest, kappa is about 0.023 second, and on the flank, 0.014 second. The

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second paragraph under Activity 8.3.1.17.3.3.1 (in Section 3.13.5 of this progress report) describes the implications of low kappa values for ground motion estimates at Yucca Mountain.

Shallow velocity profiles have been used to derive in situ seismic velocities at the Yucca Mountain site. The few reliable geotechnical investigations available, however, yield dynamic properties that are not consistent with the in situ velocity measurements. The only data base for dynamic response of tuffs consists of laboratory measurements on similar tuff deposits from Los Alamos, New Mexico. Yucca Mountain tuffs have not been tested, and very few test results on tuffs have been reported; hence, an empirical data base is not available. As shear strain increases from dynamic loading, shear modulus degrades and material damping decreases—effects that can produce potential ground motion amplification. Site amplification factors from the nonlinear properties associated with volcanic tuff could increase predicted ground motions, specifically at frequencies near 1 Hertz, as much as 25 percent.

Activity 8.3.1.17.3.4.2 - Model site effects using the wave properties of the local geology. The objective of this activity is to develop a calibrated theoretical site-effects model for use in extrapolating the observations documented in Activity 8.3.1.17.3.4.1 to locations and depths where ground-motion predictions are needed, but where instrumental recordings are not available.

This activity has been completed.

Forecast: Project staff will help plan and support the probabilistic seismic hazard analysis.

3.13.7 Study 8.3.1.17.3.5 - Ground Motion at the Site From Controlling Seismic Events

The objective of this study is to identify the controlling seismic events and to characterize the resulting controlling ground motions. Controlling seismic events are those underground nuclear explosions or earthquakes that would generate the most severe ground motions at the site at frequencies of engineering significance.

Activity 8.3.1.17.3.5.1 - Identify controlling seismic events. The objective of this activity is to identify underground nuclear explosions or earthquakes that would produce the most severe ground motions at the site at frequencies of engineering significance. There may be more than one controlling seismic event because different events may generate the most severe ground motions in different frequency bands.

No progress was made during the reporting period. Inputs from Activity 8.3.1.17.8.6.3: Probabilistic Seismic Hazard Analysis, are needed to support this activity.

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Activity 8.3.1.17.3.5.2 - Characterize ground motion from the controlling seismic events.

The objective of this activity is to generate suites of strong-motion time histories and corresponding response spectra representative in amplitude, frequency content, and duration of site ground motions that could be generated by the controlling seismic events.

Much of the framework for the characterization of ground motions from controlling seismic events is summarized in the chapter on vibratory ground motion cited above for Activity 8.3.1.17.3.3.1 (Section 3.13.5 of this progress report), and in the studies that are referenced therein.

Forecast: Project staff will assist in planning and supporting the probabilistic seismic hazard analysis. FY 1997 activities include developing a methodology to determine the controlling earthquake from the Probabilistic Seismic Hazard Analysis and other information.

3.13.8 Study 8.3.1.17.3.6 - Probabilistic Seismic Hazards Analyses

The objectives of this study are to quantify (a) the probability of experiencing ground motions of varying degrees of severity that might result from earthquakes of varying magnitudes and distances from the potential repository site, and (b) the potential for fault displacements of varying degrees of severity to disrupt the surface facilities or the underground repository. (Note that this study combines the objectives originally designated for Studies 8.3.1.17.3.6 and 8.3.1.17.2.1, Section 3.13.2 of this progress report).

Activity 8.3.1.17.3.6.1 - Evaluate ground-motion probabilities. The objectives of this activity are to (a) quantify the probabilistic vibratory ground motion values appropriate for seismic design of the potential repository structures, systems, and components, and (b) provide documentation of the bases for these determinations sufficient for regulatory review and licensing.

See discussion under Activity 8.3.1.17.3.6.2.

Activity 8.3.1.17.3.6.2 - Assessment of fault displacement hazard. The objective of this activity is to assess the fault displacement hazard for repository design.

Discussions of this activity and the previous activity are combined because much of the completed work or work in progress pertains to the study as a whole. Project scientists coordinated the preparation and review of a report that describes the seismotectonic framework and the characterization of faulting at Yucca Mountain (Whitney, 1996). The introductory chapter summarizes the history of seismotectonic studies in the Yucca Mountain area and the regulatory and design requirements and technical issues involved in site characterization. The report contains 11 chapters that discuss the results of the several major areas of investigation that obtained essential information on tectonism and seismicity that may affect repository performance.

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The topics in the report (a) identify and characterize faults, both at Yucca Mountain and in the surrounding areas, with emphasis on faults with demonstrable Quaternary activity; (b) determine the distribution and geochronology of Quaternary deposits; (c) calculate amounts, rates, and recurrence intervals of Quaternary fault displacements; (d) estimate earthquake magnitudes and recurrence rates at Yucca Mountain; (e) locate and characterize relevant earthquake sources; and (f) develop tectonic models.

Because many of the data and interpretations presented in the report were obtained in one or another of the several studies and activities in the preclosure tectonics program (Section 3.13), summaries of the content of various individual chapters are given under the appropriate study and activity headings in this progress report. Each of these topical investigations provides critical data for use in evaluating ground motion and fault displacement hazards at Yucca Mountain, and will be fully applied to achieve those objectives.

Chapter 5 of the synthesis report (Pezzopane et al., 1996) utilizes paleoseismic data (as presented in Chapter 4 of the synthesis report; see Whitney and Taylor, 1996) to formulate three models of earthquake recurrence and estimate paleoearthquake magnitudes for Yucca Mountain faults. Descriptions of these models follow.

Model 1. This recurrence model assumes that each large-displacement paleoearthquake (defined by a preferred displacement of ≥ 50 cm or a maximum displacement of ≥ 100 cm) on each fault is an independent event and that smaller displacement events are products of secondary or distributed faulting. Twelve large-displacement events occurred during the last 500 ky, with eight of the events between 15 ka and 150 ka. The recurrence of these large-displacement events for the past 500 ky is about 44 ky; however, the recurrence of the last eight events is much shorter, about 19 ky. Because the geologic record is more complete on each fault back to 150 ka, the 19 ky recurrence is considered more accurate for this model.

Model 2. This recurrence model assumes that each paleoseismic event, including fracturing and small displacement events recorded on each fault, is an independent earthquake. A total of 39 events are present in the 500-ky paleoseismic record. Assuming all events represent individual earthquakes, the average recurrence interval between these events is about 13 ky.

Model 3. This recurrence model attempts to correlate events on different faults using timing data and geologic constraints from the individual fault studies presented in Chapter 4 of the seismotectonic framework synthesis report (Whitney, 1996). Distributed faulting is assumed to have occurred on the basis of (a) close spacing between faults, (b) the interconnectedness of many faults, (c) the overlap of timing data for events, and (d) the patterns of primary and secondary faulting associated with historical surface-faulting earthquakes in the Great Basin. The various constraints and assumptions are used to define nine scenario earthquakes at Yucca Mountain and to describe their occurrence

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in space and time for the past 150 ky, including possible rupture distributions, minimum and maximum rupture lengths, rupture displacements, and scenario magnitudes and recurrence. The preferred moment magnitudes of these scenario earthquakes range from about M_M 6.2 to 6.9, and the time interval between the scenario events varies from 7 ± 3 ky to 25 ± 10 ky. The average recurrence interval is 17 ± 5 ky for the past 150 ky for the nine scenario earthquakes in the moment magnitude range of 6.2 to 6.9.

Chapter 9 of the synthesis report (Pezzopane and Dawson, 1996) addresses issues important to fault-rupture hazard assessments, particularly in extensional terrains such as the northern Basin and Range. Focusing on the large-magnitude ($M_M \geq 5.5$), surface-faulting earthquakes of the region, the study (a) examines the patterns, amounts, and characteristics of surface ruptures; and (b) develops relations between earthquake source properties, such as magnitude, fault dip, and focal depth, and the associated rupture patterns, such as the rupture zone lengths, widths, and displacements, splaying or branching ruptures, and fault segmentation. For local Yucca Mountain faults, fault displacement assessments rely upon site-specific geologic and paleoseismic data—measurements of the amounts, orientations, slip sense, and temporal frequencies of displacement—to constrain the size and timing of future faulting events.

Forecast: Plans will be developed to resume the probabilistic seismic hazard analysis. The plan for this analysis will be reviewed and revised if necessary. Ground motion, seismic source, and fault displacement facilitation teams will be assembled to prepare for and conduct workshops and prepare reports.

3.13.9 Study 8.3.1.17.4.1 - Historical and Current Seismicity

The objective of this study is to compile information on recorded earthquakes near Yucca Mountain. This information will be used to help identify and characterize potentially relevant earthquake sources for the probabilistic hazard analysis; to develop regional earthquake ground-motion models; and to determine local geologic and depth-of-burial effects on ground motion at the site.

Activity 8.3.1.17.4.1.1 - Compile historical earthquake record. The objective of this activity is to compile a record of historical seismic events in the southern Great Basin or within 100 km of Yucca Mountain that will indicate whether each cataloged seismic event is thought to be a natural earthquake, induced earthquake, under ground nuclear explosion, cavity collapse, or blast. For potentially damaging earthquakes ($M_M \geq 5.5$) in the study region, available information will be compiled on ground-motion intensity, availability of strong-motion records, and extent and style of faulting.

Work on this activity was completed last reporting period (ending March 31, 1996). Preparation of an expanded earthquake catalog to support the probabilistic seismic hazard analysis is discussed in Section 3.13.8 of this progress report.

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Activity 8.3.1.17.4.1.2 - Monitor current seismicity. The objective of this activity is to provide empirical information on how often earthquakes are currently occurring in the southern Great Basin; what the orientation, depth, and style of faulting are; how seismic-wave amplitudes scale with magnitude and attenuate with distance in the region; and how ground motions vary with depth and with surface geology in the site area.

Seismic monitoring of the southern Great Basin in the vicinity of Yucca Mountain continued with the digital network. The digital network covers an area with an approximate 50 km radius around Yucca Mountain. Twenty-one stations were installed on April 1, 1996; and two additional stations were added by September 30, 1996. Sites for four additional stations were located and negotiations are in progress with the Bureau of Land Management and the National Park Service for permits and approvals to install the instruments. More than 1000 earthquakes have been located within or near the digital network during this 6-month reporting period. The largest event occurred at Little Skull Mountain on September 6, 1996, at 08:16:56 (universal coordinated time) and had a local magnitude (M_L) of 3.6. The focal mechanism for this event was determined to be primarily dip-slip with some strike-slip motion along a northeast-trending fault plane, very similar to the main Little Skull Mountain event of June 29, 1992. Over 100 aftershocks of the September 6 event were located within the next few days, and several hundred aftershocks were apparent on the records of the nearest station.

The overall threshold of the digital network is approximately $M_L = -0.3$, but in the immediate vicinity of Yucca Mountain it is several tenths lower, with events as small as -0.8 having been located. Within this reporting period, 28 earthquakes have been located within 15 km of the station RPY (Figure 3-2), which lies roughly over the mid-point of the ESF tunnel; of these, 5 were within 10 km of RPY. Detailed analysis of these 5 quakes is in progress.

Tomography Using Teleseismic P Waves

Field teleseismic studies of Crater Flat were completed, and most of the teleseismic delays to stations within Crater Flat and southern Yucca Mountain can be explained by crustal variations in the upper 3.5 km that were modeled in earlier refraction studies (Study 8.3.1.4.2.1, Section 3.3.3 of this progress report). The moderate velocity variations that remain beneath Crater Flat and southern Yucca Mountain probably derive from deeper upper-crustal variations. There is no clear evidence suggesting a potential volcanic hazard (Activity 8.3.1.8.1.1.3, Section 3.6.1 of this progress report). With crustal effects removed, there is no evidence of an eastern boundary between Crater Flat and Yucca Mountain. A low-velocity region parallels the Rock Valley fault zone in the deep crust and upper mantle. Low velocities correlate with lithospheric weakness and may result from structural, petrologic, thermal, or partial-melt variations. Consistent with teleseismic imaging, preliminary surface-wave analyses suggest only small velocity contrasts in the crust. Interpretable receiver functions suggest a 30 to 35 km thick crust beneath the site.

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Network Processing Software

Some parts of the USGS Earthworm seismic network processing scheme were incorporated into the digital upgrade data acquisition software. The advantage of the Earthworm system is its recent integration with DataScope, a relational data base for processing and archiving seismic network data. The Earthworm-DataScope system is expected to simplify routine processing and provide easier access to the digital data. Estimates of near-real-time earthquake magnitudes will be more accurate and more reliable.

Monitoring UE-25 UZ#16

Triggered data are being acquired from UE-25 UZ#16 at the 100 ft (30.5 m) and 1600-foot (487.7 m) levels on two sets of three-component sensors. These are the sensors at the top and bottom of the borehole string. Numerous blasts from the Beatty area and many local earthquakes, predominantly from the Little Skull Mountain aftershock zone, have been recorded on the portable instrument at UE-25 UZ#16. Also, regional earthquakes, mostly from a number of small earthquakes in the Mammoth Lakes, California area, have been recorded both uphole and downhole. Some records of blasting activity in the Thermal Testing Facility (Figure 3-4) were also acquired. Some small earthquakes in the Yucca Mountain block that have triggered stations of the digital network have also triggered the borehole recorder. These data are valuable for estimating near-surface site effects above the ESF.

Strong Motion Network

Two site visits have been made to the strong motion network in and around Yucca Mountain. The last site visit was in June 1996, and all instruments were operating properly. Data were collected and converted to a network processing format and archived.

Tunnel Monitoring

The Field Work Instruction for the installation of a strong motion instrument in the Thermal Testing Facility has been reviewed. A mount for three FBA-11 strong motion sensors ($>1g$) was constructed, and the instruments were configured for use with portable recorders. The sensors have been tested on a tilt table and found to perform to specifications; they have also been tested with the REFTEK recorders.

Activity 8.3.1.17.4.1.3 - Evaluate potential for induced seismicity at the site. The objective of this activity is to evaluate the potential for human activity to significantly perturb natural seismic hazard at the site by inducing seismicity at or near the site. To date, the human activities that have been identified as having a potential to induce seismicity in the site region are the impoundment of Lake Mead, the testing of nuclear devices at the Nevada Test Site, and excavation of the repository itself.

Seismic monitoring within the ESF and by stations located near Yucca Mountain are providing a data base that will be used to assess the potential for excavation induced seismicity. This data collection is being performed under Activity 8.3.1.17.4.1.2.

Forecast: When permits can be obtained for the last 4 stations, the digital monitoring network will be extended to its full 27 stations. Procedures for collecting the data from this network and for routine analysis of it will be completed in early FY 1997. A procedure for handling the strong-motion network will also be implemented. The development of the data base for the seismic data and installation of software to access the data in near-real-time will continue. The Thermal Testing Facility will be instrumented with a strong-motion instrument in early October. Data from UE-25 UZ#16 will continue to be collected and analyzed. A report on the FY 1996 seismicity will be prepared. Modeling of a normal fault in foam rubber will be performed, and a report on the results should be available by January 1, 1997. The modeling work will address the effects of normal fault geometry with a shallow weak zone on near-fault strong motion.

3.13.10 Study 8.3.1.17.4.2 - Location and Recency of Faulting Near the Prospective Surface Facilities

The objective of this study is to identify a site in Midway Valley sufficiently large for surface facilities in which significant Quaternary faults are absent.

Activity 8.3.1.17.4.2.1 - Identify appropriate trench locations in Midway Valley. The objective of this activity is to identify appropriate trench locations at proposed locations for repository surface facilities that are important to safety through detailed geologic mapping.

This activity was completed, and the trench locations are documented in the report (Whitney and Taylor, 1996) discussed in Activity 8.3.1.17.4.2.2.

Activity 8.3.1.17.4.2.2 - Conduct exploratory trenching in Midway Valley. The objectives of this activity are to investigate the possible occurrence of late Quaternary surface fault rupture in the vicinity of planned surface facility locations important to safety and to identify sites without evidence of significant late Quaternary faulting. This activity will provide input into the location and design of surface facilities important to safety, particularly those associated with waste handling.

The large amount of data obtained during geologic mapping and trenching studies in Midway Valley was summarized as part of the chapter on Quaternary paleoseismology and stratigraphy (Whitney and Taylor, 1996) and included in the seismotectonic framework synthesis report for Yucca Mountain (Whitney, 1996). The proposed site for the location of the surface facilities associated with the potential repository is on the eastern side of Exile Hill, which is located on the west margin of Midway Valley. Geologic mapping and the excavation and logging of several trenches at that locality revealed the presence of three normal faults (from west to east: West Portal, East Portal, and Exile Hill faults) with down-to-the-east displacements of

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Tertiary volcanic rocks of a few meters to as much as 30 m. No evidence was observed in the trenches to indicate that the overlying surficial deposits were displaced by faulting. However, steeply dipping, northeast-trending fractures that break, but do not measurably displace the middle Quaternary and older colluvial units, were identified in trenches across the Exile Hill fault, as well as in soil pits that also span this fault. Although clear evidence of displacement is lacking, the close association of the Quaternary fractures with the underlying fault in bedrock strongly suggests that the fractures represent minor intrablock deformation of the relatively stable Midway Valley structural block that is bounded by the Bow Ridge fault on the west and the Paintbrush Canyon fault on the east. Trenches across both of the latter features provide abundant evidence of Quaternary activity, the studies of which are discussed under Activity 8.3.1.17.4.6 (Section 3.13.14 of this progress report).

Forecast: No further work is planned because the study has been completed.

3.13.11 Study 8.3.1.17.4.3 Quaternary Faulting Within 100 km of Yucca Mountain, Including the Walker Lane

The objective of this study is to identify Quaternary faults within 100 km of Yucca Mountain; and to characterize faults capable of future earthquakes with magnitude such that associated ground shaking could impact design or affect performance of the waste facility.

Activity 8.3.1.17.4.3.1 - Conduct and evaluate deep geophysical surveys in an east-west transect crossing the Furnace Creek fault zone, Yucca Mountain, and the Walker Lane. The primary objectives of this activity are to provide geophysical data and analysis that will (a) help to identify, locate, and characterize potentially significant seismic source zones; (b) characterize the crustal velocity structure and define lateral inhomogeneities in that structure; and (c) assist in determining whether buried magma bodies are present in the Yucca Mountain area.

Results of the 37-km seismic reflection survey across Crater Flat and Yucca Mountain are discussed under Activity 8.3.1.4.2.1.2 (Section 3.3.2 of this progress report). No further work is expected for this activity.

Activity 8.3.1.17.4.3.2 - Evaluate Quaternary faults within 100 km of Yucca Mountain. The primary objectives of this activity are to establish the abundance, distribution, and geographic orientation of known and suspected Quaternary faults within 100 km of the potential repository site, and to characterize those faults within this area whose apparent length or recurrence rate indicate a potential for future earthquakes of sufficient magnitude to affect design or performance of the waste facility.

A chapter on Quaternary faults in the Yucca Mountain region (Keefer and Pezzopane, 1996) was prepared for the synthesis report on the seismotectonic framework of Yucca Mountain (Whitney, 1996). Summary descriptions of 67 relevant and potentially relevant faults (depending on the evidence for Quaternary movement) (see Activity 8.3.1.17.3.1.1 in Section 3.13.3 of this progress report) are given. The selections were coordinated with geologists working on Study

8.3.1.17.3.1 (see Section 3.13.3). The fault descriptions include the principal fault parameters and emphasize the nature of the evidence for Quaternary activity. The descriptions are based on compilations by Piety (1996) and Simonds et al. (1995b), field studies of selected faults in areas adjacent to Yucca Mountain (Anderson et al., 1995a and b), and the results of paleoseismic studies of faults in the immediate vicinity of the potential repository (Study 8.3.1.17.4.6, Section 3.13.14, of this progress report).

Activity 8.3.1.17.4.3.3 - Evaluate the Cedar Mountain earthquake of 1932 and its bearing on wrench tectonics of the Walker Lane within 100 km of the site. The objective of this activity is to evaluate the relevance of the 1932 Cedar Mountain earthquake to potential sources of ground shaking and rupture in that part of Walker Lane within 100 km of Yucca Mountain.

Available data are being used in probabilistic seismic hazard analyses at Yucca Mountain (see Study 8.3.1.17.3.6; Section 3.13.8 of this progress report). No further work is expected for this activity.

Activity 8.3.1.17.4.3.4 - Evaluate the Bare Mountain fault zone. The objectives of this activity are (a) to evaluate the potential for ground shaking associated with future movement along the Bare Mountain fault zone; (b) to estimate the age of the most recent faulting on the Bare Mountain frontal fault; (c) to estimate the recurrence intervals of faulting; (d) to determine the nature and age of faulting within the fault complex east of the frontal zone, (e) to determine the nature of tectonic control of the location and orientation of the main wash in Crater Flat; and (f) to determine the subsurface configuration of fault zones.

For the seismotectonic framework synthesis report (Whitney, 1996) a section was developed to describe the Quaternary paleoseismology and stratigraphy of the Yucca Mountain site area (Whitney and Taylor, 1996). This section discusses final results of the program of surficial geologic mapping, and includes descriptions of representative soil profiles, topographic profiling of fault scarps, excavation and mapping of trenches, and numerical dating of deposits exposed in trenches conducted to determine the history of Quaternary faulting on the Bare Mountain fault zone.

The interpretations of the available data indicate that the following parameters characterize the Bare Mountain fault:

1. The most recent surface-rupturing event occurred no more recently than about 14 to 24 ka, and could be old as 100 ka.
2. Average displacement during surface-rupturing events is probably 1.0 to 1.5 m.
3. The fault is not segmented; surface rupture has occurred on all or most of its 20-km length and has occurred along a relatively linear, narrow zone.

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4. Surface-rupturing earthquakes on the fault occur infrequently. The recurrence of moderate-to-large, surface-rupturing earthquakes appears to be on the order of tens of thousands to a hundred thousand years or more.
5. The late Quaternary slip rate is quite low, on the order of 0.01 mm/year.

Activity 8.3.1.17.4.3.5 - Evaluate structural domains and characterize the Yucca Mountain region with respect to regional patterns of faults and fractures. The objectives of this activity are to map faults and lineaments within 100 km of the site and identify those with geomorphic expression indicative of Quaternary faulting; to classify the area into subareas (domains) containing relatively homogeneous faults and lineaments; to map the areal extent of desert varnish coating; and to identify areas of suspected hydrothermal alteration.

As indicated in earlier progress reports (a) a lineament map was prepared from published maps by Reheis (1991 and 1992) and Reheis and Noller (1991); (b) additional surficial deposits mapping was accomplished in Activity 8.3.1.5.1.4.2 (see Section 3.4.4 of this progress report); and (c) hydrothermal alteration will be evaluated in Study 8.3.1.9.2.1 (see Section 3.7.2 of this progress report).

Activity 8.3.1.17.4.3.6 - Analyze rotation (drag) of bedrock along or over suspected wrench faults based on rotation of paleomagnetic declinations. The objective of this activity is to determine the spatial and temporal patterns of oroflexure bending based on rotation of paleomagnetic declinations.

A discussion of vertical-axis rotations in the vicinity of Yucca Mountain is included in the chapter on the Neogene tectonic evolution of Yucca Mountain for the seismotectonic framework report (Whitney, 1996), in a section prepared by Fridrich et al. (1996). Areal variations in paleomagnetic directions were documented by determining large numbers of remanent directions from different localities in widespread ash-flow tuffs, each of which was erupted and cooled over a very short time interval. The major stratigraphic units for which paleomagnetic data were collected include the 12.7 Ma Tiva Canyon Tuff, the 11.6 Ma Rainier Mesa Tuff, and the 11.45 Ma Ammonia Tanks Tuff. The data indicate that the curved pattern of faulting southward across Yucca Mountain is the result of southward-increasing clockwise rotation. Preliminary paleomagnetic data obtained in the northwest part of Crater Flat suggest that the observed radial pattern of faulting is partly a primary feature, but it has been accentuated by westward-increasing clockwise rotation across the northern part of the basin. Thus, the variation in fault trends within the Crater Flat structural basin (which includes both Yucca Mountain and Crater Flat; see Fridrich, in press) largely reflects the pattern of vertical-axis rotation in the basin, but it also reflects localized modification of the regional stress field in the vicinity of the caldera complex at the north boundary of the basin. Much of the vertical-axis rotation reflects distributed strike-slip deformation that is superimposed on the extensional regime of the area.

Forecast: No further work is planned because this study has been completed.

3.13.12 Study 8.3.1.17.4.4 - Quaternary Faulting Proximal to the Site Within Northeast-Trending Fault Zones

The objective of this study is to evaluate the potential for ground motion resulting from future movement of Quaternary strike-slip faults east and south of the site area.

Activity 8.3.1.17.4.4.1 - Evaluate the Rock Valley fault system. The objectives of this activity are (a) to determine the location, spatial orientation, length, width, Quaternary recurrence rate, and the location, amount, and nature of Quaternary movement of the Rock Valley fault system; and (b) to estimate the total displacement, including strike-slip and dip-slip components, of Quaternary datums.

A final report on the Rock Valley fault system was included as a section in the chapter on Quaternary paleoseismology and stratigraphy of the Yucca Mountain site area (Whitney and Taylor, 1996) for the seismotectonic framework synthesis report (Whitney, 1996). The results of recent trenching activities, radiometric age determinations, and related studies are presented, together with the results of earlier work discussed in previous progress reports. The combined data lead to the following principal conclusions:

1. The Rock Valley fault zone is a locus of ongoing fault slip that has been punctuated by large, ground-breaking earthquakes. Repeated, clustered, low-magnitude ($M_L < 4.0$) earthquakes within Rock Valley and adjacent terrain indicate that the fault zone is presently active. Strike-slip and oblique slip occur from near-surface to about 15-km depth.
2. On the basis of the short recurrence interval of less than 10 ky between the most recent (< 3 ka) and penultimate (< 12 ka) surface-rupturing events and on the recent seismic activity in Rock Valley, the probability seems high that a surface-disrupting earthquake will occur along the Rock Valley fault system during the next 10 ky. Displaced Quaternary stratigraphic units suggest that movement during such an event will be primarily strike-slip in the range of 3 to 30 cm.

Activity 8.3.1.17.4.4.2 - Evaluate the Mine Mountain fault system. The objective of this activity is to determine the location, spatial orientation, length, width, Quaternary recurrence rate, and the location, amount, and nature of Quaternary movement of the Mine Mountain fault system.

A final report on the Quaternary history and seismic potential of the Mine Mountain fault was completed (O'Leary, 1995), and results of the study were included in previous progress reports.

Activity 8.3.1.17.4.4.3 - Evaluate the Stagecoach Road fault zone. The objective of this activity was intentionally deleted.

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The Stagecoach Road fault was evaluated under Study 8.3.1.17.4.6 (see Section 3.13.14 of this progress report); study results are discussed in the chapter on Quaternary paleoseismology and stratigraphy of the Yucca Mountain site area (Whitney and Taylor, 1996) for the synthesis report on the seismotectonic framework of Yucca Mountain (Whitney, 1996).

Activity 8.3.1.17.4.4.4 - Evaluate the Cane Spring fault system. The objective of this activity is to determine the location, spatial orientation, length, width, Quaternary recurrence rate, and the location, amount, and nature of Quaternary movement of the Cane Spring fault system.

The Cane Spring fault system was described in the seismotectonic framework synthesis report (Whitney, 1996). As indicated in previous progress reports, this fault is not considered a significant tectonic feature or to have significant seismogenic potential.

Forecast: No further field work is planned because this study has been completed.

3.13.13 Study 8.3.1.17.4.5 - Detachment Faults at or Proximal to Yucca Mountain

The objectives of this study are to supply information pertaining to distribution, displacement rate, and age of detachment faults proximal to Yucca Mountain. Key questions regarding detachment faults are whether they represent a significant earthquake source, and whether they conceal a significant earthquake source at depth. To resolve both questions, activities are focused on resolving the Quaternary behavior of postulated detachment faults.

Results of the study of detachment faults in the Yucca Mountain area are summarized in papers by Simonds et al. (1995a and 1996). As indicated in Progress Report #14 (DOE, 1996b), the Paleozoic-Tertiary contact shows no evidence of being a regional locus for detachment faulting. Geophysical evidence indicates this contact is offset by steeply dipping normal faults beneath Yucca Mountain (see Activity 8.3.1.4.2.1.2, Section 3.3.3 of this progress report). Information from the study of detachment faults is discussed in the chapter on tectonic models (O'Leary, 1996) that is included in the seismotectonic synthesis report (Whitney, 1996).

Activity 8.3.1.17.4.5.1 - Evaluate the significance of the Miocene-Paleozoic contact in the Calico Hills area to detachment faulting within the site area. The objectives of this activity are to determine whether the contact of Miocene volcanic rocks on Paleozoic strata is tectonic or depositional; if tectonic, to determine Quaternary activity, if any, of the possible detachment fault; and, if Quaternary, to determine the direction and age of movement, attitude of fault plane, and nature of deformation of the Miocene (upper plate?) sequence.

Work on this activity has been completed. As reported in Progress Report #13 (DOE, 1996j), the geologic relations indicate that the Miocene-Paleozoic contact is mostly depositional (except for a few gravity slide blocks or slabs) and shows no evidence of being a detachment fault surface. No further work will be done.

Activity 8.3.1.17.4.5.2 - Evaluate postulated detachment faults in the Beatty-Bare Mountain area. The objective of this activity is to determine if postulated detachment faults in the Beatty Bare Mountain have been active in the Quaternary.

Field mapping of the Big Dune quadrangle and the east half of the Beatty Mountain quadrangle has been completed and the maps are in preparation.

Activity 8.3.1.17.4.5.3 - Evaluate the potential relationship of breccia within and south of Crater Flat to detachment faulting. The objective of this activity is to determine whether breccias tectonically emplaced on low-angle surfaces beveled across the Paleozoic and younger strata are slide masses or near-surface parts of a detached upper plate; and, if either, how they relate to postulated Quaternary detachment faulting.

Breccia occurrences in the area originated as rock avalanches off high-angle fault scarps, and are not related to detachment faulting. The relationships and interpretations are discussed in reports by Fridrich (in press) and Simonds et al. (1995a). No further work will be done.

Activity 8.3.1.17.4.5.4 - Evaluate postulated detachment faults in the Specter Range and Camp Desert Rock areas. The objective of this activity is to determine whether the basal contact of the Horse Spring Formation is depositional or tectonic; and, if tectonic, to determine whether movement was Quaternary or older, and if Quaternary, to determine the direction and amount of offset, the amount of extension, and the style of extensional deformation of the upper plate.

Work on this activity was completed before the reporting period.

Activity 8.3.1.17.4.5.5 - Evaluate the age of detachment faults using radiometric ages. The objectives of this activity are to determine if the subdetachment basement and the Bare Mountain massif cooled through the blocking temperatures of zircon and apatite during the Quaternary Period; and to determine if the Northern Amargosa core complex cooled through the blocking temperatures of muscovite and biotite during the Quaternary Period.

As discussed previously, other studies have indicated that detachment faulting is not present at Yucca Mountain (see Study 8.3.1.4.2.1, discussed in Section 3.3.3 of this progress report.)

Forecast: This is an unfunded study, and no future work is being planned.

3.13.14 Study 8.3.1.17.4.6 - Quaternary Faulting Within the Site Area

The objectives of this study are to identify and characterize Quaternary faults that intersect or project toward the surface facility, repository, or controlled area; and to identify and characterize Quaternary faults at the site whose length or recurrence rate suggest a potential for future earthquakes with magnitudes such that associated ground shaking could affect design or performance of the waste facility.

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Activity 8.3.1.17.4.6.1 - Evaluate Quaternary geology and potential Quaternary faults at Yucca Mountain. The objectives of this activity are to synthesize and evaluate data pertaining to location, orientation, length, width, Quaternary recurrence rate, and location, amount, and nature of Quaternary movement of faults within the site area; and to identify unrecognized faults in the site area.

See the description under the following activity (8.3.1.17.4.6.2).

Activity 8.3.1.17.4.6.2 - Evaluate age and recurrence of movement on suspected and known Quaternary faults. The objectives of this activity are (a) to determine through trenching and trench wall mapping the location, spatial orientation, length, width, Quaternary recurrence rate, interconnections at the surface, and the location, amount, and nature of Quaternary movement of the Windy Wash, Solitario Canyon, Ghost Dance, and Paintbrush Canyon faults and other suspected or possible Quaternary faults within the site area; and (b) to determine through trenching and dating the age, amount, and nature of offset and the recurrence history of the Bow Ridge fault system and to evaluate that information in context with data contributed by other studies on the age, nature, and origin of fracture coatings and fissure fillings deposited within that zone.

Activities 8.3.1.17.4.6.1 and 8.3.1.17.4.6.2 are discussed together, because the results of the investigations during the reporting period pertain to Study 8.3.1.17.4.6 as a whole. A total of 52 exploratory trenches or natural exposures were excavated or cleaned in the past 20 years on faults within or in close proximity to the potential repository site area. Detailed mapping of these exposures and excavations, studies of the nature and distribution of the near-surface deposits, soils, and geomorphic surfaces, and radiometric age determinations have led to interpretations bearing on the characteristics and chronology of fault movements and seismic activity at Yucca Mountain during the Quaternary. The findings and conclusions, some of which were summarized in previous progress reports, are described in the chapter on Quaternary paleoseismology and stratigraphy of the Yucca Mountain site area (Whitney and Taylor, 1996) included in the synthesis report on the seismotectonic framework of Yucca Mountain (Whitney, 1996). The data provide direct input to probabilistic analyses of ground motion and fault displacement hazards. Brief discussions relating primarily to displacements, recurrence intervals, and slip rates on the principal Quaternary faults follow.

Northern Crater Flat fault

The Northern Crater Flat fault is a down-to-the-west, normal or normal oblique fault that trends north to northeast along the east side of Crater Flat about 5 km west of the potential repository. Only one of the two trenches excavated across the central portion of the projected trace of the fault intersected the fault. Stratigraphic and structural evidence for as many as five paleoearthquake events was observed in this trench. On the basis of a minimum age of 500 ka for the oldest exposed Quaternary unit and an estimate of less than 10 ka (preliminary age date of 5.46 ± 1.4 ka) for the most recent faulting event, a possible range in average recurrence interval is 120 to 160 ky. Cumulative displacement for all five events is about 160 cm, indicating a slip rate of < 0.003 mm/yr since the earliest event occurred.

Southern Crater Flat fault

The southern Crater Flat fault is a north- to northeast-trending normal fault, down to the west, with a left-lateral strike-slip component. Initially projected as a southern segment of the Crater Flat fault system, the fault is presently considered a splay of the Windy Wash fault. Two trenches were excavated across the southern Crater Flat fault, exposing alluvial gravel deposits that contain accumulations of fine-grained eolian material. There is evidence that at least three paleoseismic events occurred during the Quaternary, with a total measured offset of 24 to 65 cm. Preliminary age determinations of the alluvial materials and of opaline silica collected from the inner rinds of clasts indicate the oldest event occurred 130 to 250 ka, the next 10 to 60 ka, and the youngest 2 to 6 ka. Minimum recurrence intervals are in the range of 5 to 60 ka, and the estimated maximum vertical slip rate is 0.002 mm/yr.

Windy Wash fault

The north-trending Windy Wash normal fault, with down-to-the-west displacement of a few hundred meters in bedrock, is located about 4.5 km west of the potential repository. Three trenches were excavated across scarps in alluvium along the central part of the fault. One trench displays evidence of eight coseismic surface ruptures during Quaternary time and the other two display evidence of five ruptures. Dating of soils and fine silt deposits indicate that the surface faulting along the Windy Wash fault took place about 3, 40, 75, 150, 200, 240, 340, and 400 ka (preferred values or mid-points of the ranges of event timing). The recurrence interval of faulting for the last four events is about 40 to 50 ky, and between 50 to 57 ky for the longer record; the preferred recurrence interval is 40 ky. Total net displacement on the oldest hanging wall deposit is 3.7 m, which indicates a long-term average slip rate of 0.01 to 0.0116 mm/yr.

Fatigue Wash fault

The Fatigue Wash fault is a north- to northeast-trending down-to-the-west, normal to normal-oblique slip fault located about 2.5 km west of the potential repository. Three to six paleoseismic events (five is the preferred number) are documented by the stratigraphic and structural relations exposed in two trenches excavated in Quaternary deposits along the fault trace. Four of the preferred number of events occurred after 730 ka. The two most recent events probably took place between 20 and 70 ka, suggesting a late Quaternary clustering of earthquake events. An estimate of the long-term average recurrence interval ranges from 120 to 250 ky, with a preferred value of 185 ky. Two meters of cumulative vertical displacement during the last four events indicate a Quaternary slip rate of 0.002 ± 0.001 mm/yr. Data from measurements on scarps outside the trenches indicate a greater Quaternary slip rate of 0.009 ± 0.006 mm/yr.

Solitario Canyon fault

The Solitario Canyon fault is the main north-trending normal fault that bounds the west side of the structural block occupied by Yucca Mountain and lies close to the western edge of the potential repository. Displacement along most of the fault trace is down to the west, with offsets in bedrock more than 500 m in places. Eleven trenches and one natural wash exposure have been

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excavated across or near the Solitario Canyon fault, exposing evidence that suggests as many as four paleoseismic events dated at 20 to 30, 70 to 80, 120 to 200, and 150 to 250 ka, respectively, took place along the fault. There is also an indication that two episodes of fracturing postdate the most recent of these events; these fracturing episodes are interpreted as being most likely associated with moderate-sized earthquakes on the Solitario Canyon fault or related to earthquakes on nearby or regional faults. Characteristics of the affected surficial deposits suggest that the fractures developed in Holocene and/or latest Pleistocene time. A recurrence interval of 35 ky is considered a minimum (two events within the past 70 to 80 ka, and four within the past 150 ka). Current estimates of 1.8 to 2.4 m cumulative displacement over 150 to 250 ky indicate the average mid- to late-Quaternary slip rate is within the range of 0.007 to 0.016 mm/yr, with a preferred rate of 0.011 mm/yr.

Ghost Dance fault

The Ghost Dance fault trends north-south through the center of the potential repository. It is a subvertical to steeply west-dipping normal fault with down-to-the-west dip-slip displacement of bedrock ranging from 21 to 47 m. Four trenches have been excavated in Quaternary sediments across projected traces of the Ghost Dance fault, but no offset of any of these deposits has been observed. In one of the trenches, for example, 40 to 50 cm of unfaulted latest Pleistocene to early Holocene (age range 82.8 ± 1.9 to 9.6 ± 0.1 ka) slope-wash colluvium and fine-grained eolian deposits can be seen to overlie faulted and fractured bedrock. A discontinuous fracture, however, was observed in one of the lower units of the thin surficial sequence that does not extend upward through the higher units. The fracture may have resulted from a seismic event on any number of faults in the area; age relations suggest that the fracturing must have occurred at least 82 ka.

Bow Ridge fault

The Bow Ridge fault is a prominent north-striking, west-dipping normal fault that bounds the east side of the structural block occupied by Yucca Mountain and displaces bedrock more than 100 m. The fault is well exposed in places along the west side of Exile Hill, where a series of trenches has been excavated to reveal a complex fault zone developed in highly fractured Tertiary volcanic rocks and Quaternary alluvial deposits. Several faulting events are evident in the surficial units, the oldest more than 700 ka and two younger events 130 to 150 ka and 30 to 130 ka, respectively. Cumulative dip-slip displacement of the Quaternary deposits ranges from 30 to 45 cm (considering oblique-slip component, net slip is 33 to 70 cm). Preferred values for average recurrence intervals of faulting events range from 100 to 140 ky. Slip rates vary from 0.002 to 0.007 mm/yr, with a preferred value of 0.003 mm/yr.

Paintbrush Canyon fault

The Paintbrush Canyon fault lies along the east side of Midway Valley and is the easternmost of the major north- to northeast-trending normal faults in close proximity to Yucca Mountain (within 4 km of the potential repository). Estimates of down-to-the-west displacements of Tertiary volcanic rocks range from 250 to 500 m. Paleoseismic studies at three

sites—natural exposures of sand ramps on the west side of Busted Butte and one trench each at Fran Ridge and Alice Ridge—indicate that multiple Quaternary displacements have occurred. Age determinations for the various events vary from one site to another, with the most recent event ranging from 5 to 90 ka and the next youngest ranging from 70 to 150 ka. Possibly as many as five faulting episodes occurred during earlier Quaternary time. Measurements of net slip displacements also vary widely between individual events and from one study site to another, with preferred values ranging from 28 to 167 cm for a single Quaternary event. Preferred values of recurrence intervals and slip rates, based on the combined age data for all three study sites, range from 20 to 120 ky and 0.002 to 0.025 mm/yr, respectively.

Stagecoach Road fault

The Stagecoach Road fault is a northeast-trending normal fault at the southeastern corner of Yucca Mountain, about 10 km south of the potential repository. The amount of bedrock displacement is estimated to be 400 to 600 m down to the west, and trench excavations display evidence of several episodes of Quaternary faulting. The two youngest events have been dated as taking place 5 to 15 ka and 20 to 30 ka, respectively. Possibly two earlier events occurred in late Pleistocene time. The age relationships indicate preferred values for recurrence intervals in the range of 10 to 35 ky and slip rates of 0.03 to 0.05 mm/yr.

Abandoned Wash, Pagany Wash, and Sever Wash faults

Trenches were excavated across Abandoned Wash, Pagany Wash, and Sever Wash faults; all three are in close proximity to the potential repository. No evidence of Quaternary activity was observed in these trenches.

Forecast: One additional trench on the Ghost Dance fault will be recommended.

3.13.15 Study 8.3.1.17.4.7 - Subsurface Geometry and Concealed Extensions of Quaternary Faults at Yucca Mountain

The objectives of this study are to provide data on the distribution of mass, magnetic gradients, geoelectric features, and seismic velocities and reflections that will aid in evaluating the continuity of Quaternary faults where concealed by Holocene and late Pleistocene surficial deposits; to evaluate the data and its limitations; to evaluate the possibility that Quaternary faults exposed as high-angle faults at the site continue to depth as planar, high-angle faults, or alternatively, flatten at depth and merge with one or more long-angle faults; and to provide information on continuity of rock units within the repository and controlled area to assist the investigation of site geology.

There will be no study plan developed for this study and the eight associated activities. Field geophysical surveys and analysis of the subsurface geometry and concealed extensions of Quaternary faults are to be performed under Study 8.3.1.4.2.1 discussed in Section 3.3.3 of this progress report. Geophysical surveys conducted for Study 8.3.1.4.2.1 will be examined as inputs

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for assessing concealed faults and subsurface geometries. The implications of subsurface geometry and concealed extensions of Quaternary faults will be addressed as part of the evaluations associated with Study 8.3.1.17.3.6, discussed in Section 3.13.8 of this progress report.

Forecast: No further work is planned under this study.

3.13.16 Study 8.3.1.17.4.8 - Stress Field Within and Proximal to the Site Area

The objective of this study is to provide data on ambient stress at the site and its immediate vicinity that will aid in evaluating most favored orientation and nature of future movement on faults within the site area, stability of potential pathways for radionuclide travel controlled by or related to fracture aperture, the stability of mined excavations, response of rock mass to thermal loading, and applicability of tectonic models. A secondary objective is to evaluate the potential relevance of paleostress data to prediction of future stress orientations.

As originally described in the SCP, four activities were included in Study 8.3.1.17.4.8, but because (a) the objectives and parameters assigned to two of the activities are very similar, and (b) tasks assigned to the other two activities are adequately covered by Study 8.3.1.17.4.12 (Section 3.13.20 of this progress report), the scope of this study is now limited to one activity.

Activity 8.3.1.17.4.8.1 - Evaluate Present Stress Field Within and Proximal to the Site Area. The objective of this activity is to measure the vertical and lateral variation of in situ stress at and proximal to the potential repository by conducting hydraulic fracturing stress measurements and observations of stress-induced borehole breakouts in boreholes that are scheduled to be drilled adjacent to the site. The magnitudes and orientations of the horizontal and vertical in situ stresses are the principal parameters to be determined.

The draft study plan was prepared and is in review. The scope of the study involves in situ stress measurements in new boreholes adjacent to Yucca Mountain using the hydraulic fracturing method combined with observations of stress-induced borehole breakouts as recorded on geophysical logs.

Forecast: Further work on this study is contingent upon the drilling of new boreholes.

3.13.17 Study 8.3.1.17.4.9 - Tectonic Geomorphology of the Yucca Mountain Region

The objective of this study is to document Quaternary uplift and subsidence within the Yucca Mountain region and to evaluate regional variation in the nature and intensity of Quaternary faulting.

There will be no study plan developed for this SCP section and no work is being planned. The work scope will be transferred to and performed under Studies 8.3.1.5.1.4 (Section 3.4.4 of

this progress report) and 8.3.1.17.4.12 (Section 3.13.20 of this progress report). Data to describe the characteristics and parameters of tectonic features were collected under Studies 8.3.1.17.4.3 (Section 3.13.11 of this progress report) and 8.3.1.17.4.6 (Section 3.13.14 of this progress report).

Forecast: No further work is planned under this study.

3.13.18 Study 8.3.1.17.4.10 - Geodetic Leveling

The objective of this study is to evaluate possible historical and contemporary vertical displacements across potentially significant Quaternary faults within 100 km of Yucca Mountain. Secondary objectives are (a) to characterize the historical rate of uplift and subsidence in the Yucca Mountain region and (b) to evaluate the possible existence of tectonic boundaries, coinciding perhaps with the Walker Lane or with the Furnace Creek fault zone, that may separate domains with differing rates of uplift and subsidence.

Three activities are assigned to Study 8.3.1.17.4.10: Activity 8.3.1.17.4.10.1 (Relevel base-station network, Yucca Mountain and vicinity); Activity 8.3.1.17.4.10.2 (Survey selected base stations, Yucca Mountain and vicinity, using global positioning satellite); and Activity 8.3.1.17.4.10.3 (Analyze existing releveling data, Yucca Mountain and vicinity). Because the tasks involved in conducting these activities are closely allied, statements on the progress and descriptions of the work being performed have been combined.

Results of geodetic leveling surveys in the Yucca Mountain region are discussed in a chapter on geodesy and contemporary strain in the Yucca Mountain region (Keefer et al., 1996) which was prepared for the seismotectonic framework synthesis report (Whitney, 1996). Existing first-order level lines are located along Highway 95 between Beatty and Las Vegas, and along a 92-km traverse that extends from Highway 95 north-northeast across Crater Flat, east across Yucca Mountain, southeast across Jackass Flats and between Skull and Little Skull Mountain, across Rock Valley, and ends back on Highway 95 south of Mercury. In addition, quadrilateral networks were established across several of the major faults at Yucca Mountain.

Periodic surveys of the level lines and quadrilaterals show no changes in the elevations of benchmarks that can confidently be attributed to fault movements, except in response to the June 29, 1992, Little Skull Mountain earthquake ($M_M=5.8$). Resurveys of the level line in the vicinity of Little Skull Mountain show that the post-earthquake benchmark elevations near Little Skull Mountain are lower than those recorded in the pre-earthquake period, with a maximum change of 22 mm observed about 2 km northwest of Little Skull Mountain. The downdropped area coincides closely with an area that lies between the southwestward projection of the Mine Mountain fault in Jackass Flats and the Rock Valley fault in Rock Valley. The observed decreases in benchmark elevations, as well as measurements obtained from a 50-km-aperture trilateration network that spans the Yucca Mountain area, closely agree with seismic records interpreted as indicating that the main shock of the earthquake involved primarily down-to-the-southeast dip-slip movement on a steeply dipping northeast-striking fault plane.

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A regional network of global positioning system stations was established jointly by the NRC, California Institute of Technology, and the Smithsonian Institute in 1991. The network consists of 15 survey sites in the Yucca Mountain and Death Valley areas. Although there is uncertainty regarding strain rates because of the short period of time involved in resurveys (1991, 1993, and 1994) preliminary results indicate two important trends in contemporary strain patterns in the Yucca Mountain region: (1) vertical and horizontal motions around the potential repository site may be present, and (2) significant horizontal (as much as 5 mm/yr) and vertical (as much as 20 mm/yr) motions are indicated along major fault zones within 50 to 100 km of Yucca Mountain (CNWRA, 1995).

Contemporary strain across the region is also being monitored by a relatively new geodetic technique, very long baseline interferometry, which allows measurements of the directions and rates of change of position of stations separated typically by distances of 200 km or more. Results to date indicate that the Basin and Range province is deforming at rates between 8 and 13 mm/yr in a direction N. 30°-45°W. relative to stations on and near the Colorado Plateau (e.g., see Dixon et al., 1995). Combined geologic, geodetic, and seismicity studies further indicate that the Owens Valley, Panamint Valley-Hunter Mountain, and Death Valley-Furnace Creek-Fish Lake Valley fault zones accommodate most of the deformation that continues northward from the Mojave Desert along what has been referred to as the eastern California shear zone, the eastern edge of which lies 50 km west of Yucca Mountain.

Forecast: Further work on this study is contingent upon the availability of funding.

3.13.19 Study 8.3.1.17.4.11 - Characterization of Regional Lateral Crustal Movement

The objective of this study is to evaluate rates and orientation of historical and current crustal strain based on analysis of existing data on seismicity, historical fault, offset, and creep in the Basin Range and at Yucca Mountain.

No unique data are required by this study. All activities were transferred to Study 8.3.1.17.4.10, discussed in Section 3.13.18 of this progress report.

Forecast: Additional data collection, if needed for this study, will be done under Study 8.3.1.17.4.10. Evaluations of data will be done, as needed, under Studies 8.3.1.17.3.6 (Section 3.13.8 of this progress report) and 8.3.1.8.2.1 (Section 3.6.3 of this progress report). Additional evaluations, as needed, will be done as parts of Study 8.3.1.17.4.10.

3.13.20 Study 8.3.1.17.4.12 - Tectonic Models and Synthesis

The objectives of this study are (a) to synthesize data relevant to tectonics; (b) to develop a model or range of models that establishes the causal relation between application of tectonic forces and formation of structures observed at Yucca Mountain and vicinity, to link observed rates of formation of structures with regional rates of crustal strain; (c) to forecast changes in

tectonic setting and the manner in which changes will affect both regional crustal strain rate and tectonic stability in the Yucca Mountain region; (d) to estimate effects of changes on rates and nature of crustal strain at Yucca Mountain and vicinity, and (e) to estimate future rates of tectonic processes at Yucca Mountain.

Activity 8.3.1.17.4.12.1 - Evaluate tectonic processes and tectonic stability at the site. The principal objectives of this activity are to synthesize geologic and geophysical data pertaining to faults (normal, detachment, strike-slip) and other structural and volcanic features in the Yucca Mountain area; and to evaluate these data in terms of the tectonic stability of the potential repository site. For additional information on the objectives, see Study Plan 8.3.1.17.4.12.

See description under Activity 8.3.1.17.4.12.1.

Activity 8.3.1.17.4.12.2 - Evaluate tectonic models. The objectives of this activity are (a) to formulate a range of tectonic models that relate the nature and estimated rates (including bounding values) of Quaternary processes (volcanism, faulting, uplift, and subsidence, lateral strain, and possibly folding) of potential significance to design and performance of the repository at Yucca Mountain; (b) to evaluate temporal changes in tectonic activity and resulting changes in fractures and other structural features of potential hydrologic significance at and in the vicinity of Yucca Mountain (relate tectonic cycle, if it exists, to tectonic model(s)); (c) to ensure that assumptions, inferences, and conclusions concerning tectonic processes that are important to design and performance of the repository are consistent with tectonic models applicable to the site; and (d) to ensure that uncertainty in the data, assumptions, and inferences concerning rates and nature of those tectonic processes that are important to design or performance of the repository is adequately reflected in conclusions about those processes.

The above two activities are treated as a single topic, because the results were combined and presented as an individual chapter on tectonic models (O'Leary, 1996) that is included in the synthesis report on the seismotectonic framework of Yucca Mountain (Whitney, 1996). The chapter describes tectonic models applicable to Yucca Mountain and its geologic setting, and discusses the support for each model that arises from analysis of the available data, including the results of geophysical investigations.

The accumulated data indicate that present seismicity in the Yucca Mountain region and basaltic volcanism are processes that involve both brittle failure to the base of the seismogenic crust and relatively rapid (quasi-elastic) response to fracturing or fault displacement. Therefore, a preferred tectonic model must involve the seismogenic crust, as well as the inferred strain behavior of the ductile middle (or lower) crust.

The various tectonic models that have been proposed for Yucca Mountain fall into three generic classes defined on the basis of bulk mechanical behavior—simple shear models, pure shear models, and lateral shear models. During the study, large amounts of geological and geophysical data were compiled and evaluated to determine which of these model types best fit the observed structural relations in the Yucca Mountain area. Conclusions are: (a) the simple shear model, which depends on detachment faulting accompanied by listric faulting as a major

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deformational mechanism, is not supported by the accumulated data (see Study 8.3.1.4.2.1 in Section 3.3.3 of this progress report); and (b) a combination of certain elements of both the pure shear model, which features horst and graben (tilted blocks) type structure, and the lateral shear model, expressed as strike-slip faulting, can be used to adequately explain the origin of the kinds of structures that are characteristic of the area.

A major factor to consider in tectonic modeling is that Yucca Mountain and adjacent Crater Flat form a half-graben (see Activity 8.3.1.4.2.1.2 in Section 3.3.3 of this progress report), termed the "Crater Flat basin" by Fridrich (in press), which is bounded on the west by the east-dipping Bare Mountain fault and on the east by a west-dipping feature known as the Gravity fault (Winograd and Thordarson, 1975). North-trending normal faults that traverse Yucca Mountain are antithetic to the Bare Mountain fault, and several of these, as well as the Bare Mountain fault, penetrate the seismogenic crust (see Activity 8.3.1.4.2.1.2, Section 3.3.3 of this progress report). Another important factor is that the Crater Flat basin structural domain lies within the Walker Lane, a zone of nonaligned structures dominated by northwest-trending right-lateral strike-slip faults and northeast-trending left-lateral strike-slip faults. Both of these types of faults are known in the Yucca Mountain area.

In summary, three major tectonic processes have given the present form and structure to Yucca Mountain and adjacent areas of the southern Great Basin: lateral extension of the upper crust, oblique shear along northwest- and northeast-trending strike-slip fault zones, and episodic volcanism that peaked in the middle-to-late Miocene time. Yucca Mountain is a direct consequence of these processes, having been constructed by a succession of tuff deposits, faulted in extension, and partly rotated by right-lateral shear.

Activity 8.3.1.17.4.12.3 - Evaluate tectonic disruption sequences. The objective of this activity is to evaluate disruption sequences involving faulting, folding, uplift and subsidence, and volcanism that are of potential significance to design or performance of the repository.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: Project staff will help plan and support the probabilistic seismic hazard analysis.

3.14 STUDY 8.3.1.20.1.1 - ALTERED ZONE CHARACTERIZATION

The Altered Zone Characterization Program was not included in the SCP. However, the changes to the program are summarized in Appendix A, Section A.1.15.

The objective of this study is to characterize the effects on the region around the potential repository that is altered by hydrothermal processes that develop in response to heating of the repository block due to radioactive decay of emplaced nuclear waste.

Activity 8.3.1.20.1.1.1 - Field and laboratory studies of the effects of mineralogical and mechanical changes on transport processes. The objective of this activity is to evaluate the impact of chemical, mineralogical, and mechanical change on hydrological properties, particularly on porosity and permeability, and the kinetics of these processes, as functions of several environmental variables, including temperature, fluid composition, fluid flow rate, stress, and water volume to surface area ratio. Also considered in these studies will be the relationship between pore geometry and permeability as recrystallization occurs within crushed, fractured, and intact materials.

Two plug-flow reactor experiments were designed, performed, and simulated using the reactive-transport code GIMRT (Global Implicit Multicomponent Reactive Transport). (See Table 6-1 for a description of the code). This work was done to ensure that the simulations reported in previous progress reports were accurate, and to obtain confidence in future simulations.

In the first experiment, Suprasil (amorphous silica) was pulverized to 125 to 75 μm size fraction, placed in a titanium cylinder 3.1-cm long with a 0.66-cm effective diameter, and infiltrated by distilled water at a flow rate of 26 mL/day for two weeks at 238°C and 84.1 bar. As silica-charged fluid exited the plug-flow reactor during progressive dissolution of the Suprasil plug, aqueous silica concentrations were systematically monitored; these attained approximately steady-state values of 300 to 320 ppm silicon ($\log a[\text{SiO}_2(\text{aq})] = -1.97$ to -1.94), well below the limit of amorphous silica saturation ($\log a[\text{SiO}_2(\text{aq})] = -1.705$) in 3 to 4 days. [Note: Although the plug-flow reactor experiment was performed at 240°C and 84.1 bar, the thermodynamic data base used in the GIMRT simulation analog is constructed for $P_{\text{sat}}(T)$, which at 240°C is 33.4 bar. However, this pressure discrepancy is insignificant (e.g., amorphous silica saturations at 240°C, 84.1 bar and 240°C, 33.4 bar are given by $\log a[\text{SiO}_2(\text{aq})]$ of -1.705 and -1.715 , respectively)].

In this experiment involving the simple system $\text{SiO}_2\text{-H}_2\text{O}$, the temperature, pressure, fluid flux ($277.4 \text{ m}^3/\text{m}^2/\text{yr}$), initial porosity (40 percent), size fraction, thermodynamic and kinetic data (Johnson et al., 1992; Rimstidt and Barnes, 1980), and outlet aqueous silica concentrations are all tightly constrained. GIMRT was used iteratively to independently calculate the specific surface area of the crushed amorphous silica, which was measured prior to the experiment. Optimal fits to the experimental data were obtained for a predicted value of $1050 \text{ cm}^2/\text{g}$, which closely agrees with Braunaur, Emmett, and Teller (BET) surface chemistry techniques used to measure specific surface area for this mineral of about $900 \text{ cm}^2/\text{g}$.

The second experiment was conducted under the same conditions as the first experiment except that crushed quartz was used in place of the Suprasil material. This quartz substitution removed the potential ambiguity associated with thermodynamic approximation of the Suprasil material as amorphous silica in the first experiment. Again, GIMRT was used iteratively to determine specific surface area of the pulverized quartz. The experimental data were most closely fit by a predicted value ($920 \text{ cm}^2/\text{g}$) that falls within the range of those determined by BET measurement.

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Close agreement between GIMRT-predicted and BET-measured specific surface areas for amorphous silica and quartz has significance beyond accuracy validation of the various plug-flow reactor measurements (fluid flux, aqueous silica concentrations, etc.) and thermodynamic and kinetic data (standard molal properties, equation-of-state parameters, dissolution rate constants, activation energies, etc.). The agreement also demonstrates the reasonableness of values used in the GIMRT simulations for several geochemical and hydrologic parameters (bulk diffusion coefficient, longitudinal and transverse dispersivity, etc.) and numerical variables (initial/maximum timestep, cementation exponent, etc.) which in many instances are imprecisely known. Sensitivity of the reactive transport calculations to variations in these variables was examined as an aid to obtaining optimal values.

Activity 8.3.1.20.1.1.2 - Evaluating existing and developing future capabilities to simulate coupled hydrothermal and reactive transport processes. The objectives of this activity are to compare codes and to evaluate their suitability for application to altered zone efforts in two steps. The first step will be to review the capabilities of the codes as they currently exist. Comparisons will be made of how the codes simulate well-documented processes. Once several codes are selected, they will be used to simulate the results of the ongoing experimental studies and to predict the outcome of those studies. They will also be used to simulate field properties of sites selected for field study. These forecasts will be used to refine modeling strategies, as discrepancies between measurement, observation, and field data become evident.

Extensive simulation efforts indicate that the OS3D/GIMRT and NUFT code packages provide the most suitable capabilities to model the processes of concern, among the code packages considered. Appendix I describes these codes, which are now in use to evaluate a variety of reactive transport concerns.

Activity 8.3.1.20.1.1.3 - Performing bounding calculations of the effect of coupled processes in the altered zone on near-field properties. The objective of this activity is to determine parameter values, limits, or ranges needed to define the waste package environment.

The effort this year has been directed toward completing reports summarizing work completed through the end of FY 1995. This effort was completed with the submittal of chapters for the Near-Field Environment Report (Wilder, 1996).

Activity 8.3.1.20.1.1.4 - Performing bounding calculations of the effect of coupled hydrological and reactive transport processes on thermal evolution. The objective of this activity is to determine the response of the altered zone over time using, as initial conditions for simulations, optional designs, and operating configuration of the potential repository.

In this study, the reactive transport simulator GIMRT (Steefel and Yabusaki, 1995) has been used (a) to accurately predict specific surface areas of amorphous silica and quartz that can be experimentally verified, (b) to predict potentially verifiable porosity and mineralogic evolution during reaction between idealized TSw2 and infiltrating fluid compositions, and (c) to model unverifiable, long-term porosity evolution in the post-emplacement altered zone. A successful simulation of dissolution experiments involving silica polymorphs provided valuable

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benchmarking for the code. Short-term, high-porosity simulations involving fluid-TSw2 interaction facilitated the necessary extension of the code to potentially verifiable systems of considerably greater compositional complexity. The use of GIMRT to simulate long-term porosity and mineralogic variation in the post-emplacement altered zone, however, demonstrates most clearly its value as a powerful investigative tool. An abundance of compositional and hydrologic approximations, assumptions, and simplifications were necessarily embodied in these still preliminary models; nevertheless they serve to elucidate the fundamental time scales (months to thousands of years) and geochemical processes (e.g., cristobalite for quartz replacement) likely to govern active evolution of the altered zone. The models can also be used to imply the distant-future porosity distributions that are critically important. As described earlier, initial modeling efforts suggest that post-emplacement reactive transport will lead to porosity enhancement in the altered zone, most dramatically in the condensation zone overlying the repository. Further modeling of fluid transport to regions below the emplacement drifts will evaluate the extent to which flow barriers may form due to porosity reduction.

These initial results are preliminary, and the predictions require considerable refinement. Advances are expected in reactive transport theory, numerical methods, computer science, reaction kinetics, and thermodynamic and kinetic data on the modeling side, and improved understanding of the pre-emplacement fluid-rock chemistry, hydrologic parameters, and associated heterogeneities of the Tpt from site-specific field data; as those advances become available, they will be incorporated in the modeling effort.

Forecast: Descriptions of the conditions under which barriers or preferential flow pathways may form will be refined. Activities will concentrate on conducting detailed reactive transport simulations and testing the simulations using a small suite of experiments to verify the applicability of the simulation results.

CHAPTER 4 - REPOSITORY DESIGN

INTRODUCTION

The Yucca Mountain Site Characterization Project (Project) is presently engaged in a comprehensive site investigation program to confirm the suitability and adequacy of Yucca Mountain as a potential geologic site for high-level radioactive waste disposal. The repository design activities are being conducted consistent with the eventual design, licensing, and construction of a Mined Geologic Disposal System (MGDS) (commonly called a geologic repository), if the site is found to be suitable.

Advanced conceptual design, completed last reporting period and discussed in Progress Report #14 (DOE, 1996b), involved the development of a design concept or concepts believed workable and capable of meeting the repository performance objectives. The design effort has now shifted to support for major upcoming Civilian Radioactive Waste Management Program (Program) milestones (viability assessment, environmental impact statement, site recommendation, and license application). This effort will build on the work performed for the advanced conceptual design.

In addition to validating design concepts, the Project has begun to better define the level of design detail required to support the viability assessment and the level needed for license application design. This process involves activities such as refining the preliminary set of design basis events. Analysis of design basis events will also be used to refine the list of repository and waste package systems, structures, and components subject to quality assurance (QA) requirements and to help determine the level of design detail required to support the viability assessment and the license application. The major activity this reporting period in support of this task was the development of a preliminary hazards analysis. Twenty-two external events (caused by factors not directly related to repository operation or worker error) were selected for further analysis, and 30 events were eliminated as inapplicable to the preclosure repository period. Depending on the probabilities and consequences projected for these events, some or all of the events subject to further analysis may eventually be determined to be design basis events. Evaluation of 60 internal events (events that are directly related to repository operation) was also begun. Analysis may determine that some of these events will be considered to be design basis events. The repository and waste package designs must be demonstrated to protect the health and safety of the public and the repository workers against unacceptable consequences of design basis events.

Design Approach

Rather than releasing one or more comprehensive updates to the advanced conceptual design, the Project plans to develop an evolving design to support the 1998 viability assessment. The evolving design will also support the environmental impact statement, the site recommendation, and the license application that will be submitted following the viability assessment. Efforts will focus directly on (a) supporting these three major Program milestones, (b) developing and identifying a current design to support post-closure performance evaluations,

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and (c) addressing likely regulatory issues associated with first-of-a-kind aspects of the repository and waste package designs. This design will be developed over a five-year period to a level of detail that will be adequate to support licensing, but not to a level of detail adequate for construction. The design to support construction will be developed later.

This design approach requires and will include the following elements to ensure its success:

- Control and documentation of design evolution. The "current" design will be updated on an ongoing basis, with the latest design for each system, structure, and component documented. A design drawing and document list will be developed and summarized to support the viability assessment. Later, detailed design descriptions for systems, structures, and components will be developed for use and reference in the license application. The level of detail in these descriptions will vary, depending on the category of the item (as discussed later in the introduction).
- Traceability of design requirements and design solutions. The Project will continue to ensure that regulatory requirements are readily traceable to the design solutions that meet those requirements.
- Documentation of design decisions and alternatives considered. Alternatives to designs selected will be discussed for design features important to waste isolation as required by 10 CFR Part 60.
- Focus on solutions for regulatory issues. The design effort will be focused on resolving issues that could affect the ultimate licenseability of the repository.

Support for Viability Assessment

The design supporting the viability assessment will build on existing design work documented in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b) and will emphasize the key technical questions that affect waste containment and isolation, performance, and cost. Design elements critical to determining the feasibility and performance of the repository and the engineered barrier system will be addressed. The effort will evaluate the technological feasibility of the designs of selected systems, structures, and components, but will generally not develop the design detail needed for licensing. Particular emphasis will be placed on designing systems and components that may be significant performance or cost drivers for the repository. The key cross-cutting technical issues for which progress toward resolution must be achieved in order to have a viable design to support the viability assessment are listed below.

- Thermal loading range
- Engineered barrier system (EBS) performance enhancements
- Criticality control concepts
- Emplacement drift ground support concept

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- Performance confirmation concept
- Retrievability concept
- Confirmation of waste handling capability
- Disposal of site-generated waste
- Strategy for mapping the repository subsurface
- Postclosure performance standards
- Viability of underground remote control concepts
- Burnup credit limits and regulatory strategy for disposal criticality
- Repository seals requirements and concepts.

Complete resolution of these issues is not required to support the viability assessment. However, the design plan to license application is a "one-pass" design, and sufficient progress toward resolution of these issues is necessary to minimize cost and schedule issues associated with redesign.

Scientific investigations and performance assessment activities will provide data and requirements for the design effort. Applicable data will come from scientific and engineering tests and analyses in the Exploratory Studies Facility (ESF), as well as from surface-based and laboratory testing and analysis. In turn, the updated total system performance assessment in support of the viability assessment will use the updated design concepts and the analyses of available site and engineering data. The primary objective of the total system performance assessment is to evaluate the probable behavior of the potential repository. An additional objective is to further refine evaluations of repository performance under a range of normal conditions and under conditions imposed by potentially disruptive events, such as earthquakes and volcanism. The performance assessment will also evaluate the possible range of performance caused by uncertainty in estimating key factors such as ground-water flow, thermal effects, and corrosion.

Establishing the Regulatory Basis

In conjunction with the effort in support of the viability assessment, the Project will support the eventual license application by identifying appropriate acceptance criteria for important systems, structures, and components. The effort will also determine the level of design detail appropriate for supporting the license application. The following categories are planned, in descending order of design detail required:

- Category 3: Systems, structures, and components with radiological importance and for which there is no regulatory precedent
- Category 2: Systems, structures, and components with radiological importance but for which regulatory precedent exists
- Category 1: Systems, structures, and components with no radiological importance

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Efforts in support of viability assessment will focus primarily on Category 3 systems, structures, and components, and those impacted by the key technical issues previously described. The Project will use a "Board of Consultants" made up of experts in the area of design support for licensing to provide independent input on the process and help ensure the effort is properly focused and executed. This Board began providing input on repository issues this reporting period, as discussed later in this introduction.

Design Phases

Using the results of the categorization process just described (which has also been referred to as "binning"), the design will be developed in three phases. The first phase will support the viability assessment as previously described. The design process for this phase will include the following:

- Making major decisions to support performance assessment (e.g., determine waste package materials)
- Determining materials for repository construction (e.g., whether and how to use concrete)
- Obtaining initial test results for important issues such as taking credit for galvanic protection of the waste package
- Determining basic repository parameters such as layout, thermal loading, and drift diameter
- Establishing basic design requirements for the majority of systems, structures, and components.

This phase will emphasize development of "Category 3" systems, structures and components. It will also emphasize design work required to support the total system performance assessment for the viability assessment.

In the second phase, the design will be developed to support the license application, the environmental impact statement, and the site suitability recommendation. This phase will include detailed design to support licensing for "Category 3" systems, structures, and components. "Category 2" items will be developed to less detail (preliminary analyses, partially dimensioned drawings, and outlined specifications). "Category 1" items will contain the least amount of detail (analysis methodologies, sketches, or undimensioned drawings, and identification of specifications).

The third phase of design will focus on areas identified as needing resolution of questions or issues that emerge in the licensing process. Residual design of "Category 3" and further development of "Category 2" and "Category 1" items will continue to support construction.

Design Activities This Reporting Period

Design activities focused on validating design concepts through refined analyses and testing and improving the layouts and operations concepts developed during advanced conceptual design. Important progress that resulted from this effort included the following:

- The repository layout was revised to make better use of the available emplacement area, as discussed in Section 4.1.6. The proposed position of the central exhaust drift was lowered from the upper block emplacement drift plane to some (as yet not firmly established) distance below that plane. This change would allow the elimination of area needed under the advanced conceptual design as thermal buffers on either side of the exhaust drift, as well as area needed at the emplacement drift level for the exhaust drift itself. The tunnel boring machine launch main that was part of the previous design was found to be unnecessary because of a change to the tunnel boring machine launch and recovery concept. These two changes would add about 100 acres of potentially usable emplacement area, which would eliminate the need to use the proposed lower emplacement block east of the Ghost Dance fault. This east block area, however, would still be available for use as a contingency.
- A revised emplacement concept, discussed in Section 4.1.8, was developed. It is expected to reduce cost by using a gantry crane to emplace waste packages on pedestals in the emplacement drifts. This approach would save the costs associated with purchase and emplacement of over 10,000 railcars.
- A study of engineered barrier system concepts was issued as discussed in Section 4.1.19. The study reached several conclusions based on assumptions about site, repository, and waste package characteristics current at the time the report was developed. The conclusions were also based on assumed repository performance objectives because there are currently no overall repository performance objectives applicable to Yucca Mountain. First, the study concluded that neither backfill nor other engineered barrier enhancements would be required to meet the assumed repository performance objectives. Without engineered barrier enhancements, the study results indicated significant margin to the performance objectives out to 10,000 years. The study also examined performance beyond 10,000 years and concluded that the repository without engineered barrier enhancements would meet the assumed performance objectives well beyond 10,000 years, though perhaps with a smaller margin. Given the uncertainties in predictions for very long time periods (thousands to tens of thousands of years), the results of this study should be viewed as indicators of performance trends more than as accurate predictors of the repository's ability to meet performance objectives in the very distant future.

Neither backfill nor any other engineered barrier enhancements are currently planned to be included in the design to support the viability assessment, though such enhancements will be reconsidered as important new information becomes available. Conclusions about the need for backfill or other enhancements could change because of improved

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understanding of the site and design. Therefore, the study recommended that a design requirement be levied to provide a sufficient design envelope such that a backfill emplacement system could be designed and incorporated later.

The results of this study will be reconsidered if appropriate as the Project's understanding of site characteristics such as percolation flux evolves and as the regulatory performance objectives to be applied to Yucca Mountain become clear.

- A thermal loading study was produced that re-examined the validity of several previously established thermal goals, as discussed in Section 4.1.16. The study had several recommendations:
 1. A temperature goal for the TSw2/TSw3 interface should be deleted in favor of a goal of a 90°C limit at the average top of the zeolite layer. This new goal should help ensure that irreversible alterations do not occur in the zeolite layer, which may have an important effect on repository performance by retarding the flow of radionuclides from degraded waste packages to the water table. Because the distance from the emplacement area down to the top of the underlying zeolitic unit varies over the repository area, an average distance will be used in the application of the thermal goal. This distance is not yet defined, but is estimated to be approximately 170 m below the repository block. Using this fixed value may result in some portions of the upper reaches of the zeolitic unit, which are closer to the emplacement area than the average, exceeding the 90°C goal. This approach is considered adequate, however, to provide overall protection for the unit.
 2. Temperature goals for fuel cladding and emplacement drift walls should be retained.
 3. Temperature variations caused by differences in waste package heat outputs should be suppressed through thermal management techniques such as varying waste package spacing within drifts, ventilating emplacement drifts, and modifying waste package heat outputs by aging or fuel assembly selection. (Aging would likely require interim or substantial lag storage at Yucca Mountain. The current repository design does not include these features.)
 4. There would be little repository performance benefit to increasing the thermal loading near the edges of the repository to make up for heat losses there that would cause waste packages very near the repository edge to be cooler than those closer to the center.
 5. The repository design should not be changed to accommodate placing waste packages very close together in drifts, a concept referred to as "line loading."

Under assumptions used to develop the study, the study concluded that the advanced conceptual design repository thermal loading (83 MTU/acre) may support meeting

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repository performance objectives, but these predictions have not been verified. Because of the uncertainties still present in thermal and overall repository performance analyses, however, the study recommended that at least one alternative thermal loading (36 MTU/acre) be retained as a contingency in case future analyses indicate that the higher thermal loading is not the right choice. Although there is no compelling reason to change a low thermal loading, the Project will continue to maintain flexibility in the design to allow a change should future evaluations indicate low thermal loading is necessary. Also, as with other studies, the results of this study will be reconsidered if appropriate as the Project's understanding of site characteristics evolves.

- An MGDS concept of operations document was issued, which revises previous concepts of operation to reflect design work to and beyond the advanced conceptual design. This document, discussed in Section 4.4.2, also incorporates updated system description information.
- Surface design activities focused on the preparation of two analyses. The first was the Uncanistered Fuel Receipt and Handling Analysis (CRWMS M&O, 1996p), which identified surface facility design and cost impacts related to the deletion of the multi-purpose canister concept. The report concluded that the Waste Handling Building size and required operations staffing would increase. The second was the Internal Design Basis Events Analysis (CRWMS M&O, in prep.[a]) which analyzed design basis events for surface facilities and developed safety-related design data (e.g., frequency of occurrence, radiological releases, and dose analyses). The results of the analyses were input into the Preliminary MGDS Hazards Analysis described earlier in this introduction. Work also was started on the Waste Handling Operations Systems Configuration Analysis. This report will establish the configuration of the waste handling surface facilities, recommend either a dry (hot cell) or a wet (fuel pool) waste handling technology, and determine the number of operating lines needed to meet required throughput.

Repository Consulting Board

In June 1996, the ESF Tunneling Board of Consultants transitioned at the Project's suggestion from focus on ESF activities to work with the repository program as the Repository Consulting Board. The Board's charter is to provide recommendations to the Project in the following aspects of repository design:

- Ground support
- Tunnel stability
- Constructability and operability
- Waste emplacement and retrievability.

The Board met three times during this reporting period: June 24-25, August 26-27, and September 19-20, 1996. During these visits the Project briefed the Board on the status of the repository design. The Board has prepared a final report on the June meeting and a draft report

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for the August and September meetings. In these reports the Board has made several constructive suggestions. The Project has extensively discussed these suggestions with the Board in subsequent meetings and is incorporating them into the design for the repository that will support the viability assessment. The Board has praised the depth and quality of the design team and their responsiveness to the Board's recommendations and suggestions.

4.1 CONFIGURATION OF UNDERGROUND FACILITIES (POSTCLOSURE) (SCP SECTION 8.3.2.2)

Development of layout concepts for the geologic repository operations area continued and will continue into the next period. Section 4.1.6 discusses layout analyses performed this reporting period.

4.1.1 Design Activity 1.11.1.1 - Compile a Comprehensive List of All the Information Required From Site Characterization

The objective of this design activity is to summarize, in one document, all the information required from site characterization for repository surface and subsurface design.

The Repository Design Data Needs report (CRWMS M&O, 1995c), discussed in Progress Reports #13 (DOE, 1996j) and #14 (DOE, 1996b), considers the design data needed to support various levels of design, when the data are needed, and the adequacy of existing data. The report was used this reporting period as a basis for identifying repository design data needed from the ESF drift-scale heater test. Specific data needs listed in that document that apply to the heater test are as follows:

- Deformation around openings
- Convergence of openings
- Ground support load and deformation
- Rock temperature change.

Additional data beyond those identified in the Repository Data Needs Report were identified as being needed for repository design, including long-term material properties, especially concrete properties, at elevated temperatures. Information is also needed on long-term chemical interactions between concrete and the natural rock/ground-water environment, especially in determining the pH of such a system. These needs are being addressed by work being done within the Project.

Forecast: The Repository Design Data Needs Report will continue to be incorporated into Program planning and to provide the basis for developing more detailed data gathering activities. Continued design activities may result in additional data needs being identified, and other data needs being eliminated. Data needs identified will continue to be provided to the Test Coordination Office for disposition. Revisions to the Design Data Needs Report are not planned.

4.1.2 Design Activity 1.11.1.2 - Determine Adequacy of Existing Site Data

The objective of this design activity is to determine whether the available site data are sufficient for licensing. If not, it will be determined whether additional data must be gathered or whether the design can be completed using assumed parameters until additional data has been collected. This is an ongoing determination up to submittal of the license application.

This activity is closely related to Design Activity 1.11.1.1, discussed in Section 4.1.1 of this progress report. Revision 00 of the Repository Design Data Needs Report (CRWMS M&O, 1995c), described in Progress Reports #13 (DOE, 1996j) and #14 (DOE, 1996b), contains the analyses of sufficiency of available site data.

In this report, the level of data completeness required for the various stages of repository design was compared with the present level of completeness. The term "completeness," used as a measure of the adequacy of data needed for the various stages of repository design, was defined using the following descriptors:

- Substantially Complete: Sufficient data are available and additional analysis or collection is not likely to significantly change the results or conclusions. Data variability, a combination of measurement uncertainty and inherent randomness (e.g., spatial distribution), is reasonably defined.
- Bounded: Realistic bounding values, with upper and lower extremes identified, have been established for data at this level. Data variability is moderately defined.
- Conservative: Data are sufficient to estimate credible extreme or worst-case values, conditions, or assumptions. Data variability is approximately defined.

The effects of elevated, long-term temperature effects on concrete were assessed using a literature search. This assessment resulted in data with a conservative level of completeness. As identified under the previous design activity (1.11.1.1), specific test data are needed to establish material behavior for the expected in situ conditions at a higher level of completeness.

In an effort to provide guidance for selecting repository construction materials suitable for postclosure conditions, the Project is working to develop an acceptable concrete formulation with a relatively low pH. Lower pH is desirable because it reduces the likelihood or severity of long-term geochemical effects caused by degraded concrete. Such effects could adversely impact the ability of the repository to impede radionuclide transport. Early indications are that compositional changes are possible that will reduce the pH below that of standard cement formulations. Data supporting this conclusion are at a conservative level of completeness. A higher level of completeness will be needed to fully resolve this issue.

The completeness of some geologic data [specifically related to data needs 2.1.2 Rock Stratigraphic Units, 2.2.1 Bedding Structure, and 2.2.2 Faults (CRWMS M&O, 1995c)] has been

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improved by additional U.S. Geological Survey surface bedrock mapping, mapping in the ESF, borehole logging, and surface fault mapping.

Forecast: The adequacy of data will be continually assessed to support ongoing design activities. Qualification of existing and new data will be emphasized.

4.1.3 Design Activity 1.11.1.3 - Document Reference Three-Dimensional Thermal/Mechanical Stratigraphy of Yucca Mountain

The objective of this design activity is to produce reports that describe the three-dimensional thermal and mechanical stratigraphy of Yucca Mountain. The description will rely on information gathered from site characterization activities and will be entered into the Reference Information Base (DOE, 1995m). The description will then be used as the reference basis for design and performance assessment. This activity is related to Design Activity 1.11.3.2, discussed in Section 4.1.7 of this progress report.

Progress on this design activity during the reporting period can be divided into two parts: (1) the definition of the thermal/mechanical units in the Topopah Spring Tuff, and (2) the development of the three-dimensional computer model. The results of these activities, discussed in the following paragraphs, have been used as input to repository design.

Definition of the thermal/mechanical units

During the last reporting period, work was begun on better defining the thermal and mechanical properties of the repository host rock within the Topopah Spring Tuff. Previous definitions were based on projections from very limited data. With the drilling of the North Ramp Geologic boreholes (NRG series) and the Systematic Drilling boreholes (SD series), the thermal and mechanical information data base for these rocks has increased significantly. Currently, the categories of data include the following:

Mechanical Properties Data

Porosity
Bulk density
Grain density
Compressive strength
Tensile strength
Static Poisson's Ratio
Static Young's Modulus
Wave velocity

Thermal Properties Data

Thermal conductivity
Thermal expansion

Data from each of these categories were summarized on depth plots to reveal any differences in characteristics between the previously identified thermal/mechanical units. Particular emphasis was placed on the TSw1/TSw2 contact, which has been the subject of some

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discussions in the past [see Design Activity 1.11.1.3 in Progress Report #14 (DOE, 1996b)]. For all repository design activities, the TSw1/TSw2 contact is identified as lying within the crystal-poor, upper lithophysal zone (Tptpul) of the Topopah Spring Tuff (Buesch et al., 1996a). This TSw1/TSw2 contact is identifiable on geophysical density logs, in core, in the ESF, and in outcrop. Generally, the TSw1 rocks above the contact exhibit many small lithophysal cavities with a fractured matrix, while the TSw2 rocks below the contact exhibit larger and fewer lithophysal cavities with a hard, compact matrix. This contact is gradational and is generally 5 to 40 m above the top of the crystal-poor, middle nonlithophysal zone (Tptpmn) of the Topopah Spring Tuff, which had been previously identified as the nominal TSw1/TSw2 contact. Table 4-1 shows the relationships just described.

Analysis of the thermal and mechanical data is still in progress, but preliminary review of the plots shows that the portion of the upper lithophysal zone within the TSw2 unit (above the middle nonlithophysal zone) is very similar in mechanical and thermal properties to the lower lithophysal zone within the TSw2, and very dissimilar to the overlying TSw1 portion of the upper lithophysal zone. This is apparent in most of the depth plots for the thermal and mechanical data. Of particular importance to repository design is the fact that this comparison holds true for thermal conductivity, thermal expansion, and strength data plots. The similarity of the upper lithophysal zone to the lower lithophysal zone may provide additional depth of rock suitable for waste emplacement. Because of the gradational nature of the rock formations, this greater available depth in turn may allow more flexibility in selection of the repository location.

Development of the three-dimensional computer model

A three-dimensional computer model of the repository site area was developed to support repository design work. This model, designated YMP.MO3, was built using the Lynx Geoscience Modeling System (LYNX) and is an update from the previous model YMP.MO2 developed in 1995. The model incorporates new outcrop information along Solitario Canyon (Day and Miller-Corbet, 1995), new drilling and revised stratigraphic picks from core logs (CRWMS M&O, 1996e), and revised surface faults (Day et al., in prep.[b]). Changes from the previous model include covering a larger area and extending northward to Pagany Wash fault rather than stopping at Drill Hole Wash fault. (Figure 4-1 shows these two fault structures.) The stratigraphic surfaces modeled include the tops of the following units:

- TSw1 thermal/mechanical unit
- TSw2 thermal/mechanical unit
- Tptpmn lithostratigraphic unit
- Tptpll lithostratigraphic unit
- Tptpln lithostratigraphic unit
- TSw3 thermal/mechanical unit.

Also, additional features modeled include the following:

- Major faults
- Surface topography

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Table 4-1. Comparison of Lithostratigraphic and Thermal/Mechanical Units for Yucca Mountain

LITHOSTRATIGRAPHIC UNITS ^a			THERMAL/ MECHANICAL UNITS ^b
Timber Mountain Group (Tm)		Rainier Mesa Tuff (Tmr)	Undifferentiated overburden (UO)
		pre-Rainier Mesa bedded tuff (Tmrbt1)	
PAINTBRUSH GROUP (Tp)			
tuff unit "X" (Tpk)		tuff unit "X" (Tpki)	
		post-Tiva Canyon bedded tuff (Tpbt5)	
Tiva Canyon Tuff (Tpc)		crystal-rich member (Tpcr) vitric zone (Tpcrv) - nonwelded subzone (Tpcrv3) - moderately welded subzone (Tpcrv2) - densely welded subzone (Tpcrv1)	Tiva Canyon welded (TCw)
		nonlithophysal zone (Tpcrn) lithophysal zone (Tpcrl)	
		crystal-poor member (Tpcp) upper lithophysal zone (Tpcpul) middle nonlithophysal zone (Tpcpmn) lower lithophysal zone (Tpcpll) lower nonlithophysal zone (Tpcpln) - hackly subzone (Tpcplnh) - columnar subzone (Tpcplnc) vitric zone (Tpcpv) - densely welded subzone (Tpcpv3) - moderately welded subzone (Tpcpv2) - nonwelded subzone (Tpcpv1)	
		pre-Tiva Canyon bedded tuff (Tpbt4)	
Yucca Mountain Tuff (Tpy)		Yucca Mountain Tuff (Tpy) pre-Yucca Mountain bedded tuff (Tpbt3)	Paintbrush Tuff nonwelded (PTn)
Pah Canyon Tuff (Tpp)		Pah Canyon Tuff (Tpp) pre-Pah Canyon bedded tuff (Tpbt2)	
Topopah Spring Tuff (Tpt)		crystal-rich member (Tptr) vitric zone (Tptrv) - nonwelded subzone (Tptrv3) - moderately welded subzone (Tptrv2) - densely welded subzone (Tptrv1)	
		nonlithophysal zone (Tptrn) lithophysal zone (Tptrl)	
		crystal-poor member (Tptp) upper lithophysal zone (Tptpul) [upper part]	
	POTENTIAL REPOSITORY HOST HORIZON	upper lithophysal zone (Tptpul) [lower part] middle nonlithophysal zone (Tptpmn) lower lithophysal zone (Tptpll) lower nonlithophysal zone (Tptpln)	Topopah Spring welded, lithophysae-poor (TSw2)
		vitric zone (Tptpv) - densely welded subzone (Tptpv3)	Topopah Spring welded, vitrophyre (TSw3)
		- moderately welded subzone (Tptpv2) - nonwelded subzone (Tptpv1)	
		pre-Topopah Spring bedded tuff (Tpbt1)	
Calico Hills Formation (Tac)		Calico Hills Formation (Tac) pre-Calico Hills bedded tuff (Tacbt1)	

^aAfter Buesch et al. (1996b)

^bAfter Ortiz et al. (1985)

Figure 4-1. View of Potential Repository Area Showing TSw2 Thickness Contours and Fault Structures

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- Depth 200 m below the surface
- Water table surface
- Top of zeolite II surface
- Zeolite II nominal thickness
- Horizontal plane through the proposed upper repository block.

Zeolites are minerals having the capability to sorb relatively large amounts of radionuclides. Zeolite II is the designation of the layer of zeolite materials located in the lower Topopah Spring/upper Calico Hills units. The Project believes this layer may be very helpful in retarding radionuclide flow from degraded waste packages to the water table.

The LYNX three-dimensional model was used to assist in repository siting (see the discussion in Section 4.1.7 of this progress report).

Forecast: Work will continue on updating the LYNX-based model as new information warrants. Data will be entered into the Reference Information Base (DOE, 1995m) to support development of the model. Output from the model will also be entered in the Reference Information Base.

4.1.4 Design Activity 1.11.1.4 - Preparation of Reference Properties for the Reference Information Base

The objective of this activity is to develop and incorporate data into the Reference Information Base (DOE, 1995m) from sources that document pertinent repository site and design properties and describe how these properties were derived.

The Reference Information Base is a controlled data base that provides summary data and information about the project site and engineering properties. As an evolving data base, it represents the best current state of knowledge for a wide range of technical data parameters and is the primary source of approved technical reference information. The Reference Information Base provides data for engineering design and development efforts requiring specific site properties obtained from field and laboratory measurements, as well as material properties associated with waste package and engineered barrier system evaluations. Each Reference Information Base data item is formatted to present information describing the data acquisition or development methodology; the statistical bases for the displayed data, including references to source data; and the qualification status of the data.

Reference Information Base item development needs are identified in activities described in Section 4.1.1 of this progress report [which references the Repository Design Data Needs report (CRWMS M&O, 1995c)], in the Controlled Design Assumptions Document (CRWMS M&O, 1996e) that is prominently referenced throughout Chapter 4, and in the Site Characterization Plan (SCP) (DOE, 1988).

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Reference Information Base efforts in this reporting period remained focused on review of three new data items: (1) potentiometric surfaces, (2) hydrogeologic stratigraphy, and (3) thermomechanical stratigraphy. The review was continuing at the end of the reporting period, but when completed the data will be incorporated into the Reference Information Base. In addition, efforts associated with the acceptance of a data item dealing with the heat capacitance properties of TSw1 and TSw2 were in progress.

Before this reporting period, the Reference Information Base was maintained in a series of computer files, but the data were reformatted this reporting period and incorporated into the Project Table of Contents, which is a web site available for internal Project use. This change will significantly improve access to the Reference Information Base.

Forecast: Pertinent baseline data will continue to be examined for possible incorporation into the Reference Information Base. Review and incorporation into the Reference Information Base of data items for potentiometric surfaces, hydrogeologic stratigraphy, thermomechanical stratigraphy, and rock heat capacitance is planned for completion. Efforts will also be focused on review and incorporation into the Reference Information Base of specific data items necessary to support the development of the viability assessment. The electronic version of the Reference Information Base will be maintained and updated as new information is received.

4.1.5 Design Activity 1.11.2.1 - Compile Waste Package Information Needed for Repository Design

The objective of this design activity is to determine what waste package information is needed for the design of the underground facility, to obtain such data, and to document it in the Repository Design Requirements Document (DOE, 1994f).

Waste package design information provided this reporting period as an input to repository design primarily consisted of revised masses and dimensions. As discussed in the introduction to Chapter 5 and in Section 5.1.1, Subactivity 1.10.2.1.1, the number of design layouts for disposal containers has been substantially reduced since the end of advanced conceptual design. The current design for pressurized water reactor fuel is a disposal container for 21 spent nuclear fuel assemblies. This disposal container is 1.650 m in diameter and 5.335 m long. The mass of the container alone (including closure lids but not waste) has been calculated to be 33 900 kg, and the total mass of disposal container and waste has been calculated to be 50 300 kg (CRWMS M&O, 1996q). Filler material is currently thought unnecessary as a criticality control measure, so the mass of filler material has not been calculated. The disposal container for 44 boiling water reactor assemblies is 1.604 m in diameter and 5.335 m long (CRWMS M&O, 1996r); its mass will be calculated in the near future. The current design of a container for defense high-level waste would have a capacity of five defense high-level waste glass canisters, and as discussed in Chapter 5, possibly U.S. Department of Energy (DOE)-owned spent nuclear fuel. The mass and dimensions of this disposal container are currently under consideration. Masses and dimensions of disposal containers for canistered fuel will be uncertain until the geometry of the fuel canister is determined.

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Tolerances have not been taken into account in determining the waste package masses and dimensions just discussed, so these values are subject to change. Because of the design and construction of the container, most of the clearances that will be added will tend to increase the waste package diameter rather than the length.

Forecast: Development of waste package design information is an ongoing effort, and the information needed for and used in repository design will be updated as changes occur. This design activity will continue to report design information needed and provided for repository design as a result of the waste package design process.

4.1.6 Design Activity 1.11.3.1 - Area Needed Determination

The objective of this design activity is to determine the waste emplacement area required for the underground facility. Area needed is an important input to repository layout design and is also an important input in determining the suitability of the site for emplacing up to 70 000 MTU of high-level waste. The area needed is compared with the usable area (discussed in Section 4.1.7 of this progress report) to make this determination. Issues such as repository layouts and allowable waste package spacing are included in this activity.

Repository design work focused on improving the "efficiency" of the subsurface layout in terms of minimizing the amount of nonemplacement area required. Although complete quantitative information is not yet available, the following observations can be made regarding planned adjustments to the layout presented in the advanced conceptual design.

The areal mass loading used for the advanced conceptual design was 83 MTU/acre. This value is being reassessed in light of the change in thermal goals discussed in Section 4.1.16. A range of 80 to 100 MTU/acre is being carried forward into the current design. At 83 MTU/acre, the theoretical area required for emplacement of 70 000 MTU of waste is 843 acres, as described in Progress Report #14 (DOE, 1996b). The advanced conceptual design layout required full use of the "upper block" west of the Ghost Dance fault and a portion of the "lower block," located in the primary area east of the Ghost Dance fault, to accommodate the 70 000 MTU inventory. Because a significant amount of internal ramping and main development would be required to provide access to this area, an effort was undertaken to determine if the lower block could be eliminated from the layout. Two layout changes were made that collectively could increase available emplacement area enough to allow emplacing all 70 000 MTU of waste in the upper block, thus leaving the lower block area undeveloped. This area would still be available if needed for expansion due to one or both of the following eventualities: a decrease in the areal mass loading, and/or a loss of emplacement area caused by unexpected ground conditions.

The first layout change involves the lowering of the central exhaust drift. The advanced conceptual design layout showed this drift in the plane of the upper emplacement block, intersecting each of the 158 emplacement drifts. The revised layout would locate this drift below the plane of the upper block. The exhaust drift would be connected with each emplacement drift by a vertical internal shaft, or "raise," bored between the underlying exhaust drift and each

emplacement drift. The net effect of this change is the recovery of approximately 66 acres of potential emplacement area that previously had been occupied by the thermal buffers needed on both sides of the exhaust drift, as well as the area occupied by the drift itself.

The second layout change was the elimination of the tunnel boring machine launch main. The advanced conceptual design layout showed this main drift developed parallel to, and 40 m offset from, the east service main (current ESF main drift). The tunnel boring machine launch and recovery concept has been changed to eliminate the need for the tube launching/transport mechanism shown in advanced conceptual design, thus the launch main could be eliminated, resulting in the gain of approximately 35 acres of potentially usable emplacement area.

Forecast: Repository layouts will continue to be updated and refined as additional information becomes available from design efforts and site characterization. An analysis defining the repository subsurface layout to support the viability assessment is in progress and will be completed during the next reporting period.

4.1.7 Design Activity 1.11.3.2 - Usable Area and Flexibility Evaluation

The objectives of this design activity are to

1. Analyze the three-dimensional structure and stratigraphy of Yucca Mountain to identify usable areas and ensure that sufficient area is characterized to allow design flexibility
2. Produce graphic cross sections and maps that can be used to lay out the drift arrangements
3. Compare drift arrangements to ensure that they fit the geology and structure
4. Identify site geologic data requirements for determining usable area.

This design activity is closely related to and builds on work performed under Design Activity 1.11.1.3, discussed in Section 4.1.3 of this progress report. This design activity also helps determine the suitability of the site for emplacing up to 70 000 MTU of radioactive waste.

During this reporting period, a new three-dimensional computer model of the repository site area was developed under Design Activity 1.11.1.3 (see Section 4.1.3 of this progress report). The new model was developed using the Lynx Geoscience Modeling System (LYNX) and reflects new outcrop information along Solitario Canyon (Day and Miller-Corbet, 1995), new drilling and revised stratigraphic picks from core logs (CRWMS M&O, 1996e), and revised mapping of surface faults (Day et al., in prep.[b]). The new model covers a larger area than the previous model (CRWMS M&O, 1995d), extending northward to Pagany Wash Fault.

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Using this new three-dimensional computer model, the potential lateral extent for the repository was identified by sectioning the model with a cutting plane corresponding to the inclined plane of the repository. This section illustrates the maximum lateral extent to which the repository can be extended within the defined plane. The limiting criteria are as follows:

Upper limits:

Surface 200 m below the topographic surface
Top of the TSw2 thermal/mechanical unit.

Lateral limits:

60 m standoff from Type-I faults (120 m on west side of Ghost Dance fault).

Lower limits:

30 m above the top of the TSw3 thermal/mechanical unit
Static ground-water level.

These limits will be applied in the future to develop a revised estimate of useful emplacement area.

Forecast: Work will continue on extending the use of the LYNX-based model to define the available repository siting area. The available area will be modified as the model is updated.

4.1.8 Design Activity 1.11.3.3 - Vertical and Horizontal Emplacement Orientation Decision

The objective of this design activity is to provide the performance evaluation to document the decision on emplacement orientation. Well before this reporting period, the decision was made to proceed on the design assumption of horizontal in-drift emplacement.

Progress Report #14 (DOE, 1996b) contains a discussion of the emplacement mode presented in the Advanced Conceptual Design Report (CRWMS M&O, 1996b). That mode involved horizontal in-drift emplacement using a permanently committed railcar both to move the waste package to its emplacement position and to provide support. This required emplacing the railcar with the waste package. Work conducted since the release of the advanced conceptual design has led to a refinement of the emplacement methodology. The waste packages would still be emplaced horizontally in-drift, but a pedestal concept is being developed to provide waste package support. A mobile gantry crane would transfer the waste packages along the emplacement drift and place them on the pedestal. The planned method of transporting the waste packages from the surface waste handling building to the emplacement drift entrance is unchanged from that described in advanced conceptual design.

As was discussed in Project Report #14, with the railcar emplacement concept, backfill was not likely to be feasible with a center in-drift emplacement mode, and if backfill is required, an off-center in-drift mode may be preferable. The Engineered Barrier System Performance Requirements Systems Study (CRWMS M&O, 1996s), completed this reporting period, concluded that emplacement drift backfill is not required for the repository to meet its performance objectives. This conclusion was based on assumptions and knowledge about site, repository, and waste package characteristics current at the time the report was developed. The need for backfill will continue to be evaluated, and will probably not be settled until a final performance standard is promulgated.

The pedestal/gantry method would result in the waste package being placed much lower in the drift, and the gantry rails being placed higher up along the tunnel walls than the method described in the advanced conceptual design. Thus should backfill be needed, a method could probably be developed to place backfill in the center in-drift pedestal-emplaced drifts. The Project is keeping the backfill option open in repository design.

A design analysis describing the methodology of selecting the gantry/pedestal emplacement concept was being prepared and will be finalized early in FY 1997.

Forecast: Both repository and engineered barrier system designers will continue to evaluate the issues of waste package support mechanism and emplacement equipment design and methodology. The issue of emplacement drift backfill will require additional evaluation when a new repository performance standard is promulgated. A design analysis describing methods of backfilling emplacement drifts is scheduled to be issued.

4.1.9 Design Activity 1.11.3.4 - Drainage and Moisture Control Plan

The objective of this design activity is to provide postclosure designs for the layout of the underground facility to limit the amount of water in contact with the container (emplaced waste package) and, by so doing, to provide a favorable containment and isolation environment. The objective is not only to limit the amount of water in contact with the waste packages, but also to promote the movement of moisture away from the waste emplacement areas.

No new design work in the area of water movement and drainage control has been performed since the release of advanced conceptual design. The repository subsurface concept currently planned for use in support of the viability assessment incorporates a similar areal mass loading and emplacement drift arrangement to that shown in advanced conceptual design. The measures to control water movement, including slight gradients in both emplacement drifts and mains to promote gravity flow of water away from waste packages, are also still planned to be used in the design to support the viability assessment. Minor changes have been made in the main drift arrangement, though not for moisture control; but the arrangement still adheres to the basic drainage concept.

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Two systems studies performed during this period have implications for water and moisture control: the Engineered Barrier System Performance Requirements Systems Study Report (CRWMS M&O, 1996s) and the Thermal Loading Study for FY 1996 (CRWMS M&O, 1996t).

The Engineered Barrier System Performance Requirements System Study evaluated the impact on long-term performance of using various types of emplacement drift backfill materials and configurations. The primary benefit of backfill noted in the study was that backfill is predicted to result in a longer containment time for radioactive waste. The presence of backfill was found to result in a longer period of higher temperatures and lower relative humidities on the waste package surface during the heated portion of the postclosure period as compared to the no-backfill case. Corrosion of the waste packages, which is the primary mechanism responsible for the creation of pathways allowing the migration of radionuclides out of the waste package, is greatly inhibited in lower humidity environments. Another potential benefit of backfill, if used, would be to delay and minimize contact of water with waste packages after closure. However, this function requires further investigation. In this study, multiple performance assessment evaluations were developed to determine differences in predicted performance between backfilled and unbackfilled repository scenarios. Calculations of long-term repository performance that made no use of engineered barrier system performance enhancements indicated significant margin to the 10,000-year performance standard used in this study. The study, therefore, concluded that, while backfill shows promise in enhancing repository performance, it is not needed. Uncertainties remain regarding total system performance and the nature of the long-term performance standard to be applied to Yucca Mountain. Therefore, the study recommended that repository design be compatible with design and backfitting of a reasonable backfill emplacement system should emplacement drift backfill be found necessary at a later date.

The Thermal Loading Study for FY 1996 examined the thermal characteristics of waste package arrangements similar to the advanced conceptual design as well as a "line load" concept in which waste package spacing is reduced and emplacement drift spacing is increased. This line load concept concentrates the waste heat into lines separated by cooler areas. This concentration of heat would affect the movement of moisture within the host rock, and it potentially could lengthen the "above boiling" period after closure. The study concluded that, while the line load concept may have benefits, there is currently no compelling reason to change to that concept. Also, the concept has disadvantages, such as potentially higher peak drift wall temperatures, as compared with the advanced conceptual design. Thermal loading is discussed in more detail in Section 4.1.16 of this progress report. The line load concept is discussed in more detail in Sections 5.2.1 and 5.2.3.

Forecast: As subsequent phases of repository design progress, options for controlling moisture movement will be evaluated for their potential to improve repository performance.

4.1.10 Design Activity 1.11.3.5 - Criteria for Contingency Plan

The objective of this design activity is to provide criteria for the development of a contingency plan to deal with unexpected conditions that may be encountered during site characterization and repository construction. Examples of unexpected conditions that may be encountered include small zones of perched water, localized heavy fracture zones, water recharge pathways, and localized heavily lithophysae-rich zones.

As it has evolved since the release of advanced conceptual design, the repository layout continues to possess a high degree of flexibility to adjust to changes in concept, as well as to unexpected geologic conditions. The change to a pedestal-based emplacement concept maintains flexibility by allowing waste package movement within an emplaced drift using the emplacement gantry. With this concept, waste packages could be relocated within a drift, or recovered and moved to adjacent drifts, without having to first relocate or remove other waste packages.

Flexibility to Deal With Unexpected Loss of Emplacement Area

As described in Progress Report #14 (DOE, 1996b), the layout possesses a large degree of flexibility to adjust to losses of emplacement area. As discussed in Section 4.1.6 of this progress report, layout adjustments have allowed the lower block to be eliminated as an emplacement area; thus the entire lower block area (approximately 170 acres of potentially usable emplacement area) would be available as an expansion area if emplacement area is lost in the upper block. This area provides an estimated 20 percent contingency should it be needed.

Expansion Area North of Drill Hole Wash

As noted in Progress Report #14, the area north of Drill Hole Wash is being re-examined for possible incorporation into the primary repository area, but at the close of this reporting period, no decision had been made on the use of this area.

Forecast: Work on this activity will continue through FY 1997 and through progressive phases of repository design. The potential repository block definition will continue to be examined as information is received from site characterization activities. As more information on geologic structures is acquired, adjustment and possible expansion of the primary emplacement area will be considered. A decision on use of the area north of Drill Hole Wash will be made early in FY 1997.

4.1.11 Design Activity 1.11.4.1 - Chemical Changes Resulting From the Use of Construction Materials

The objective of this activity is to quantify the chemical changes (e.g., change in pH) that result from the use of a given quantity of construction material (e.g., cement).

To provide guidance for the selection of repository construction materials that will be suitable for postclosure conditions, the Project is working to develop an acceptable concrete formulation with lower pH than that of "standard" concrete. Reducing the normally very high pH of the concrete may result in enhanced ability of the repository to retard radionuclide transport. Early indications are that compositional changes to control pH are possible. A promising approach appears to be using a certain percentage by weight of silica fume. Whether or not the pH can be sufficiently reduced to alleviate possible long-term effects of concrete on radionuclide transport is not yet known. Also, adding silica fume changes some concrete properties. Strength, for example, may be increased, while Young's modulus remains essentially unchanged. The resistance of concrete to aggressive chemicals, such as sulphates and chlorides, is increased, thus making concrete with silica fume a more durable material. Because the workability of concrete decreases with higher percentages of silica fume, organic plasticizers may be required. The potential effect of these plasticizers on repository performance has not been studied.

Forecast: Further study of corrosion processes and in situ thermal testing of potential ground support components are parts of current tasks for FY 1997. Understanding of the degradation of materials during preclosure should enable an assessment of the impact on the long-term geochemical environment in emplacement drifts.

4.1.12 Design Activity 1.11.4.2 - Material Inventory Criteria

The objective of this design activity is to establish appropriate limits on the inventory of materials that will be used in construction and operation of the underground facility and to write criteria for the appropriate limits on the inventory of materials, including backfill, that will be left in the openings after decommissioning. Materials in the repository potentially affect geochemistry and therefore potentially affect waste package and repository performance. This design activity is closely related to and builds upon Design Activity 1.11.4.1, discussed in Section 4.1.11 of this progress report.

Materials that may be introduced into the repository for construction purposes are currently being evaluated. In particular, precast concrete segments are being studied as the principal means of emplacement drift permanent ground support. Precast segments would be installed in a single operation without the use of other ground support materials. The selection of precast concrete is not finalized, and cast-in-place concrete and steel sets/lagging are also being considered, although a precast concrete invert would be part of any selected system. Drifts other than the emplacement drifts are expected to be constructed with varying amounts of rock bolts, wire mesh, shotcrete, and cast-in-place concrete. The formulation of acceptable cementitious materials for repository use is currently under development, as discussed in Section 4.1.11 of this progress report.

Forecast: Work on the design and formulation of ground support materials, especially cementitious materials, will continue for FY 1997 and results will be used in the development of material inventory criteria for the potential repository. An inventory of committed materials (materials to be left in the repository after closure) will be prepared.

4.1.13 Design Activity 1.11.4.3 - Water Management Criteria

The objective of this design activity is to establish appropriate limits on the amount of waste that will be used for surface and underground facility construction and operation.

No work has been performed for this activity during the reporting period. Related work concerning water management for ESF construction and testing and surface-based testing activities is reported in Section 6.21 of this progress report.

Forecast: No work is planned for this activity in the next reporting period. For related work, see the forecast in Section 6.21 of this progress report. Water management criteria for the potential repository will be developed at the appropriate point in repository design and prior to commencement of repository construction. Criteria for water use in dust suppression, ground support installation, and fire protection will be input to the design that supports the 1998 viability assessment. These criteria are scheduled to be developed by the end of FY 1997.

4.1.14 Design Activity 1.11.5.1 - Excavation Methods Criteria

The objective of this design activity is to examine excavation methods available for repository construction and to identify constraints on those methods arising from postclosure performance considerations. The objective is to limit excavation-induced changes to rock mass permeability.

The majority of the information on excavation methodologies presented in the MGDS Advanced Conceptual Design Report and discussed in Progress Report #14 (DOE, 1996b) is still current. Several minor excavation-related changes being considered are discussed here.

Central Exhaust Drift

The central exhaust drift, as depicted in the advanced conceptual design, was located such that it intersected all 158 emplacement drifts in the upper block. This drift was to be driven in segments using a mechanical excavation device called the "mobile miner." The mobile miner is based roughly on the tunnel boring machine cutting concept in that it uses disc cutters to break the rock and grippers to hold the machine in place and allow the required large force to be applied against the rock face. A mobile miner has been built and operated in three different applications worldwide with limited success.

A change to the repository advanced conceptual design layout is being considered in which the central drift would be placed below the plane of the emplacement drifts rather than within the plane of these drifts. (See Section 4.1.6 of this progress report for further discussion of this potential change.) This configuration would allow the central exhaust drift to be excavated during pre-emplacement development using a much more efficient and cost-effective tunnel boring machine operation and eliminating the need for the mobile miner. Even in the advanced conceptual design concept this central drift could have been developed using a tunnel boring

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machine, but the tunnel boring machines could have to pass through the already-excavated, larger diameter, central drift during excavation of each emplacement drift. This situation would have required the installation of temporary surfaces within the central drift for use by the tunnel boring machine grippers.

Because the central drift in the new design would be below the emplacement drifts, a vertical connection must be provided between each emplacement drift and the central exhaust drift. This connection would be developed using a proven mining technology, the "raise borer." (A "raise" is an internal, vertical or near vertical opening in an underground mine used to connect workings at different mining levels.) Raises would be bored by first drilling a pilot hole, nominally 300 mm in diameter, from the upper level down into the lower opening. A reaming head laced with cutters would be taken into the lower level opening, attached to a drill pipe extending from the upper opening to the lower through the pilot hole. The raise boring machine would rotate the reaming bit while exerting upward force, drawing the bit from the lower opening to the upper opening and creating the raise. The excavated rock from the raise-boring would fall by gravity into the lower opening where it would be loaded and hauled out. For the repository layout, the upper opening would be each of the emplacement drifts while the lower opening would be the central exhaust drift. The raises would be lined after excavation to help ensure a long service life.

Roadheaders

As was noted in Progress Report #14, a hardrock mechanical excavation method utilizing a machine called a roadheader was tested in the ESF. An alternative excavation method will be needed because approximately 10 percent of the excavation required to build the subsurface repository would not be amenable to tunnel boring machine excavation. Most of the excavation requiring an alternative is for the "turnouts" off the service mains that provide access from the service main to the emplacement drifts. The geometry and curvature of the turnouts would not be amenable to excavation by tunnel boring machines. Figure 4-2 shows the turnouts.

A larger version of the roadheader used in the ESF, the AM 105, has had reasonable success in rock similar in strength to the Yucca Mountain tuff. Another mining equipment company has introduced a hard rock roadheader concept that is scheduled to be tested in high-strength rock in the near future. Even though no results are available, multiple efforts are under way to develop advanced roadheader-type machinery that may directly apply to the Yucca Mountain project.

Forecast: Activity on this task will continue through FY 1997 and through progressive phases of repository design. Further development and refinement of the emplacement layout design are expected, and primary and secondary excavation methods will continue to be evaluated as the design evolves. The progress of the prototype hardrock roadheaders will be monitored to gauge their success and applicability to the Yucca Mountain Project.

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Figure 4-2. Proposed Turnouts for Connecting the Service Main to Emplacement Drifts

4.1.15 Design Activity 1.11.5.2 - Long-Term Subsidence Control Strategy

The objective of this design activity is to evaluate the potential for postclosure surface subsidence and the impact of ground movement in the vicinity of the excavations on waste containment and isolation.

The potential for postclosure surface subsidence was described in Progress Report #14 (DOE, 1996b) in terms of pillar stability. Investigation of pillar stability is a means of addressing overall repository stability rather than the stability of individual drifts. Pillar failure begins at the drifts that border it. Therefore, if the drifts are stable, it follows that the pillar is also stable. No further work was done this reporting period that specifically addressed overall pillar stability.

Subsidence is not considered a viability assessment issue because, as discussed in Progress Report #14, the low extraction ratio of the repository layout (22 to 24 percent) combined with the high strength of the host rock would be expected to produce stable pillars having very high strength-to-stress ratios. Because subsidence is generally caused by pillar failure (as opposed to drift failure), the Project has preliminarily concluded that subsidence is not a major issue. The subject of subsidence will be revisited in the development of license application design to address the specific subsurface configuration at that time.

Forecast: Evaluation of subsidence and drift stability will continue as part of an ongoing emplacement drift stability and maintenance task. Future analyses will concentrate on ground support and stability of individual drifts and will include use of a jointed rock mass model.

4.1.16 Design Activity 1.11.6.1 - Thermal Loading for Underground Facility

The objective of this design activity is to establish the allowable thermal loading as a function of waste age and burnup, and waste package emplacement concept.

The ability to meet the overall performance requirements of the proposed repository at Yucca Mountain requires that the two major subsystems (natural and engineered barriers) positively contribute to the containment and isolation of radionuclides. In addition to the postclosure performance, the proposed repository must meet preclosure requirements of (a) safe operation and (b) maintenance of waste retrieval capability. The thermal, mechanical, hydrological, and chemical behavior of the repository underground facilities must be adequately understood to determine whether both the postclosure and preclosure requirements will be met in the presence of significant thermal loads.

Laboratory and in situ thermal testing and natural analog studies are key elements in gaining an understanding of how the Yucca Mountain rock would be affected by waste emplacement. The single heater test has started and the drift-scale test is in planning. These test programs are discussed further in Chapter 5 of this progress report.

A thermal loading study (CRWMS M&O, 1996t) was completed this reporting period. Its primary objective was to consider the validity of some requirements affected by thermal loading. Based on these analyses, the thermal loading study provided recommendations for requirements to support design and to support the Program's thermal loading strategy goal of maintaining flexibility to change the design thermal loading. A change might be determined appropriate as a result of enhanced understanding of the site and/or updated performance assessment information. The study provided sufficient definition of the validity of the requirements evaluated to facilitate development of design concepts and to support life cycle cost determinations. It reevaluated and/or redefined selected thermal goals currently being used by design, and it provided recommendations as to what actions (e.g., edge loading and limiting heat variability between waste packages) are needed and should be accommodated in the design. Additionally, the study recommended what alternative thermal loads should be maintained.

In the study, the geochemical goals that call for not exceeding 115°C at the TSw2/3 and CHn interfaces were evaluated. The study found no justification for these goals. The evaluations also examined the effect of heat on zeolites with respect to the dehydration of zeolites and potential mineralogic changes using natural analog studies. The natural analog information indicated the potential for a mineralogic change of clinoptilolite, a zeolite that has good sorbing capability for numerous radionuclides, to analcime. Analcime has poor radionuclide sorbing properties, so this potential change would be undesirable from the standpoint of meeting repository performance objectives. The study made the following recommendations:

- Delete the requirement to limit the TSw3 (basal vitrophyre) maximum temperature to less than 115°C.
- Delete the requirement to limit the CHn maximum temperature to less than 115°C.
- Establish a not-to-exceed temperature of 90°C for the zeolitized tuff in the Calico Hills unit. This temperature limit is to be established at the average depth of the top of the zeolitized tuff beneath a given potential emplacement area. This temperature limit would be applied at a depth 170 m beneath the upper block of the primary area. The temperature in the zeolite above this depth would be allowed to exceed 90°C. However, only a fraction of the zeolite would exceed 90°C, so the 90°C limit is considered adequate to protect the overall zeolite layer against the effects of temperature. The average depth of the top of the zeolitized layer for potential areas outside the presently planned upper block remains to be established.

Thermomechanical analyses were conducted to evaluate whether or not the not-to-exceed temperature limit of 200°C on the emplacement drift wall was a valid criterion. The thermomechanical evaluations also considered the interaction of the emplacement drift wall rock with such potential tunnel supports as steel sets and concrete liners. The analyses indicated that the not-to-exceed emplacement drift wall temperature of 200°C should be retained.

The SCP (DOE, 1988) recommended a thermal goal of 350°C on the zircaloy cladding to preserve the spent fuel cladding as an available barrier to radionuclide release. To examine the

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performance value of the potential cladding barrier, a probabilistic cladding degradation model was developed, and total system performance calculations were conducted as part of the thermal loading study. Some simplifications were made in that stress corrosion cracking, hydride reorientation, and degradation of the fuel assemblies were not considered. Based on data available, it was assumed that a nominal fraction of cladding failed before emplacement. Results of use of the cladding performance model indicated that zircaloy cladding would be a potentially excellent barrier to radionuclide release after disposal, and total system performance prediction calculations performed in support of the thermal loading study found that taking credit for cladding would reduce predicted releases to the accessible environment by about two orders of magnitude. The results were found to be somewhat temperature sensitive, and therefore the recommendation was made to retain the not-to-exceed cladding temperature of 350°C.

Previous evaluations had established that waste packages emplaced in the edges of the potential repository would cool and rewet substantially faster than packages in the center of the repository. Evaluations were performed for the 1996 thermal loading study to determine whether increasing the density of packages near the repository edges (local areal mass loading) would improve performance. The results of the analysis showed that increasing the areal mass loading at the edges would not substantially improve performance in terms of releases to the accessible environment. In addition, the increase would likely result in drift wall and cladding temperature goals being violated. Thus, the study recommended that increasing loading at the edges not be considered.

Large variations in waste package and drift wall temperatures are estimated to occur as a result of the expected potentially large variability in waste package heat output. These large temperature variations may result in overstress conditions in local areas of the near field. Additionally, the study predicted that high moisture fluxes may occur at the cooler packages because of moisture being moved from the hotter to the cooler packages. The study concluded that this temperature variability must be significantly reduced. Although the intent of the study was not to advocate a particular design solution, the study did evaluate such solutions as varying waste package spacing, ventilating the emplacement drifts, and implementing selection of waste packages/aging. Line loading (moving the waste packages close together) warrants additional study but was not recommended at this time based on the results of the evaluations, which included concerns that line loading would result in higher waste package and drift wall peak temperatures than those expected for the advanced conceptual design. Preliminary analysis cited in the study indicates that the 200°C drift wall temperature goal could be exceeded for the line load design, but further work is needed and is occurring to provide a more precise temperature estimate. Ventilation has potential but should not be much more than a natural ventilation flow (about 1 m³/s or less) and may involve some operational issues that need to be resolved. Currently, the most effective approach to reducing temperature variability appears to be reducing waste package heat output variability by selecting packages for emplacement on the basis of a target heat output and/or aging of the packages. This approach would require that some interim surface storage or aging capability be established. Current project plans do not include this capability.

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Current models predict that the advanced conceptual design thermal load of 20.5 kgU/m² (83 MTU/acre) may support meeting repository performance objective requirements, but these predictions have not yet been verified. Thermal tests are under way to provide the information to help verify the analytic models. However, the results of these tests will take some time to obtain. To mitigate the risk that the thermal tests could discover some unexpected and undesirable effects or that other performance objectives could be imposed, the thermal strategy (CRWMS M&O, 1995e) recommended that an alternative thermal loading be considered. The 1996 thermal loading study evaluated the impact of carrying such an alternative. The study recommended that, although a firm decision on thermal loading should be made as soon as practical after sufficient thermal testing results are available, the option of implementing an alternative thermal loading should be maintained until that decision is made. The study recommended an alternative thermal loading of 36 MTU/acre, a loading that would keep the boiling fronts from coalescing and thereby would allow shedding of mobilized liquid between emplacement drifts. It determined that sufficient area (at least up to a total of 1220 hectares [3015 acres] of emplacement area) may potentially exist, using the primary emplacement area and other optional expansion areas, to emplace the 70 000 MTU of spent nuclear fuel and defense high-level waste.

At present, there is no compelling reason to believe that a change to low thermal loading is necessary, and making such a change would increase the cost of the repository. However, the Project plans to continue evaluating repository performance and testing requirements for high thermal loading and to maintain flexibility in the design to accommodate lower thermal loadings. If future evaluations indicate the need to pursue a lower thermal loading, resources will be applied as needed.

The 1996 thermal loading study did not intend to recommend a single thermal loading that would meet safety requirements. Instead, the study intent was to examine issues associated with thermal loading, in general, and to identify an alternative to the high thermal loading options that would ensure sufficient flexibility exists in the Program to deal with future changes in understanding of site and repository performance. The study did, however, recommend that thermal loading of the potential repository should be limited to no more than 22.2 kgU/m² (90 MTU/acre) to avoid violating geochemical criteria on the zeolites, emplacement drift wall temperature criteria, and cladding temperature criteria. Thermal test results and verified models will be needed to establish, with a high level of confidence, whether the performance of any of the thermal loading options meets the safety standards.

Forecast: The thermal loading strategy will continue to be refined as it is implemented in the engineering, site, and regulatory areas. The recommendations of the 1996 thermal loading study will be considered in the revision of the requirements documents and integrated into the repository planning process. The study results will be reconsidered if appropriate as the Project's understanding of site characteristics evolves. As the results of in situ thermal tests, laboratory tests, and natural analog studies become available, they will be used to validate models to predict the thermal behavior of the natural and engineered systems. This process will allow a decision to be made before license application on the thermal loading of the potential repository.

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4.1.17 Design Activity 1.11.6.2 - Borehole Spacing Strategy

The objective of this design activity as originally planned was to develop a strategy for spacing waste packages within the repository that included emplacement boreholes and drifts containing the emplacement boreholes. As stated in Progress Report #11 (DOE, 1995i), however, Project planning has changed from emplacement of waste packages in boreholes to in-drift emplacement of waste packages. Thus, the objective now is to develop a strategy for the spacing of emplacement drifts and waste packages within the drifts. Drift and waste package spacing have a major impact on temperatures in and around the waste packages and in the repository as a whole. These two parameters can be adjusted to obtain a desired repository thermal loading or to achieve design goals for temperature or humidity.

This activity is closely related to Design Activity 1.11.6.1, discussed in Section 4.1.16 of this progress report. The emphasis in that activity, however, is on developing an overall repository thermal load and related goals and constraints, while the emphasis in this activity (1.11.6.2) is on developing the details to achieve the selected thermal load and meet the established thermal goals and constraints. This activity is also related to the waste emplacement management concepts discussed in Sections 4.1.6 and 4.1.8 of this progress report.

As discussed in Section 4.1.16, one of the thermal goals used to guide the repository design was eliminated, and another developed, as a result of the 1996 thermal loading systems study completed during the period. The deleted goal, $<115^{\circ}$ at the top of the TSw3, was replaced by a goal which requires that the temperature at the average distance from the repository to the top of the underlying zeolitic unit not exceed 90°C . This development occurred late in the reporting period, and this information will be incorporated into design work during the next period. The mass loading of 83 MTU/acre used in the advanced conceptual design will be reassessed using the adjusted thermal goals and either substantiated or adjusted to another value.

Forecast: Modeling of emplacement concepts such as drift spacing and waste package spacing for different thermal loadings will continue through the viability assessment design period. Factors such as the eventual maximum design thermal loading selected, the makeup of the waste package inventory, and the level of thermal loading flexibility to be maintained will all help determine the waste package spacing. Additional design evaluations are needed to determine whether aging of waste packages or selecting waste packages by heat output should be considered to mitigate waste stream variability. Additionally, design evaluations of ventilation of the emplacement drifts need to be performed and the resulting operational constraints determined. These additional evaluations will be scheduled in the course of Program planning during FY 1997.

4.1.18 Design Activity 1.11.6.3 - Sensitivity Studies

The objective of this design activity is to evaluate the effects of uncertainty in the description of the waste form and geologic setting. Recent activities have focused on determining predicted repository thermohydrologic and thermomechanical response to variations

in thermal loading. This information will be used to evaluate the adequacy of data gathered and to determine whether repository performance goals have been met with confidence.

Sensitivity studies related to the objective of this section were performed for the Engineered Barrier System Performance Requirements Study and the Thermal Loading Study for FY 1996. The results from the Engineered Barrier System Performance Requirements System Study are reported in Section 4.1.19 of this report. The results of the Thermal Loading Study for FY 1996 are reported in Section 4.1.16.

Forecast: System studies related to waste isolation requirements; seals of shafts, ramps, and boreholes; waste quantity, mix, and throughput; and the waste package size are planned for FY 1997. These studies will potentially include sensitivity analyses relevant to this design activity.

4.1.19 Design Activity 1.11.6.4 - Strategy for Containment Enhancement

The objective of this design activity is to document how design of the underground facility has taken into account containment of radionuclides, with special emphasis on obtaining better performance of the waste package containment barrier by keeping it dry.

Several options are available to enhance radionuclide containment within the waste packages or to improve calculated postclosure performance. These options include designing the engineered barrier system to enhance the waste package lifetime and taking performance credit for the fuel cladding as a barrier to radionuclide transport. Performance enhancement options were addressed in the Engineered Barrier System Performance Requirements Systems Study (CRWMS M&O, 1996s), and performance credit for cladding was addressed in the Thermal Loading System Study for FY 1996. The discussion on cladding can be found in Section 4.1.16 of this progress report. The following discusses the findings of the Engineered Barrier System Performance Requirements System Study.

The Engineered Barrier System Performance Requirements System Study evaluated the current design concept for the engineered barrier system, in concert with the current understanding of the geologic setting, to assess whether or not enhancements to the required performance of the engineered barrier system are necessary. The study's reference design concept for the engineered barrier system is described in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b). The need for enhancements was assessed by coupling the engineered barrier system with the geologic setting based on the models (some of which were updated for the study) and assumptions used for the Total System Performance Assessment - 1995 (CRWMS M&O, 1995a) and comparing the total system performance assessment results against engineered barrier system performance requirements.

Because there is currently no regulation that provides a long-term performance standard for radiological releases from the potential repository, an interim postclosure standard has been established by DOE (CRWMS M&O, 1996e). This standard requires that the probability of

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exceeding a dose rate of 15 mrem/yr not exceed 50 percent over 10,000 years when calculated for the average individual in a critical group in the Amargosa Valley area (about 30 km from Yucca Mountain). In addition, evaluations are required of the period beyond 10,000 years to gain insight regarding longer-term repository performance and to assess whether engineering measures with the potential to significantly reduce peak dose over very long time frames can be implemented at reasonable cost. The Engineered Barrier System Performance Requirements System Study evaluated doses at 1,000,000 years to be consistent with Total System Performance Assessment - 1995 and the 1995 National Research Council report on technical bases for Yucca Mountain Standards (NAS, 1995).

Subsystem performance requirements related to the engineered barrier system include (a) the derived requirement to allow no more than one percent of the waste packages to fail before 1000 years after permanent closure of the repository (substantially complete containment) and (b) a requirement to control the release rate of radionuclides from the engineered barrier system to the geologic setting (CRWMS M&O, 1996s). The study only considered, however, the overall, interim postclosure performance standard and the substantially complete containment requirement because they were most likely to impact design.

Evaluation of Current Design

The repository design considered in the study was predicted to satisfy the 10,000 year interim postclosure 15 mrem/year limit by more than four orders of magnitude, based on assumptions about site characteristics current at the time the study was developed. This design, which is given in the MGDS Advanced Conceptual Design Report, includes no backfill, drip shields, or any additional engineered barrier beyond the waste package. Excluding the potential effects of rockfall, predicted long-term performance of the repository indicated a 70 percent probability that peak dose rates at Amargosa Valley would not exceed 1×10^{-4} mrem/yr. Further, the same analysis predicted that there would be a 99 percent probability of not exceeding 0.04 mrem/yr. In addition, estimates of waste package performance indicated no breaches of waste packages would occur within 1000 years after permanent closure of the repository.

The effect of rockfall on the performance of the waste packages, and thus the performance of the repository, was estimated to result in a two-fold increase in peak dose rates at the accessible environment. A two-fold degradation in peak dose performance, however would still provide a repository that would be predicted to satisfy the maximum allowable peak dose rate over a 10,000 year period. The estimate was established by assuming that one percent of the waste packages would be breached by rockfall at the beginning of the postclosure period. This was considered a conservative assumption because waste package degradation from rockfall would probably occur over a significant period of time rather than immediately upon closure of the repository.

For time frames out to one million years, the advanced conceptual design engineered barrier system concept was predicted to yield a 50 percent probability that peak dose rates at Amargosa Valley would not exceed 10 mrem/yr. There would be a 99 percent probability that peak dose rates would not exceed 150 mrem/yr. Over this time frame, the effect of rockfall on

the performance of the waste packages, and thus the performance of the repository, was again estimated to result in a two-fold increase in peak dose rates at the accessible environment.

Given the uncertainties in predictions for very long time periods (thousands to tens of thousands of years), these results should be viewed as indicators of performance trends more than as accurate predictors of the repository's ability to meet performance objectives in the very distant future. Also, this study was based on estimates of site characteristics current at the time. The study's results will be reconsidered if appropriate as the Project's understanding of site characteristics such as percolation flux evolves.

Evaluation of Performance Enhancement Options

The various engineered barrier system performance enhancements considered included additional engineered components, as well as additional performance enhancement potentially available from existing design features but for which no performance credit is currently being taken. Both design features and performance credit options are summarized in Table 4-2.

The design/performance features described in Table 4-2 were evaluated individually and, in some instances, in combination with one another to assess their potential for enhancing performance over the one million year time frame. The results of these evaluations are summarized here.

- Including credit for spent fuel cladding in total system performance could result in an order of magnitude decrease in predicted peak dose rates at the accessible environment.
- Taking credit for galvanic protection would result in predictions of a 50 percent probability of not exceeding 0.6 mrem/yr, a 90 percent probability of not exceeding 2 mrem/yr, and a 99 percent probability of not exceeding 5 mrem/yr peak dose rate. This contrasts with a 50 percent probability of not exceeding 10 mrem/yr without accounting for galvanic protection.
- Emplacing quartz sand backfill over the waste packages at the end of the preclosure period would result in a 50 percent probability of not exceeding 0.6 mrem/yr peak dose rate at Amargosa Valley. The same analysis indicates a 99 percent probability of not exceeding 11 mrem/yr without violating any current thermal goals.
- Using quartz sand backfill, chemically treated with magnetite and lime, was found to be ineffectual over long time periods in reducing the corrosion properties of the water entering the emplacement drifts.
- Using a capillary barrier or a drip shield could result in significant reductions in the peak dose. To noticeably affect total system performance over 1,000,000 years, however, these barriers would have to perform their engineered barrier system function

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Table 4-2. Performance Enhancement Options

Design/Performance Feature	Description
Cladding	Include the effects of spent fuel cladding as a barrier contributing to control of release in performance assessment calculations
Galvanic protection of waste package	Include the galvanic protection effects in the performance assessment calculations of the corrosion allowance outer barrier of the waste package on the corrosion resistant inner barrier of the waste package
Single-layer backfill	Quartz sand/crushed tuff uniformly covering the emplaced waste packages
Chemically conditioned single-layer backfill	Treat backfill with chemical additives to condition water infiltrating the emplacement drifts to reduce its corrosion properties
Capillary barrier (e.g., Richards Barrier)	Emplace two layers of material (e.g., sloped layer of gravel below a layer of sand or silt) to divert liquid water from the waste package
Drip shield	Emplace a metallic barrier above the waste package to divert liquid water from the waste package surface
Chemically conditioned invert	Include mineral additive in the invert in order to sequester, or at least retard, radionuclide transport
Enhanced thermal protection through line loading of waste packages	Closely space the waste packages within the emplacement drifts to decrease the relative humidity and increase the temperature at the waste package surface.

for approximately 700,000 years. It would be very difficult to develop a barrier that could be demonstrated to function effectively for that long. In addition, emplacement concerns and costs associated with the capillary barriers and issues with the drip shield/waste package interface make these two concepts unattractive as engineered barrier system performance barriers.

- Using an emplacement drift invert chemically treated with a phosphate-containing sedimentary apatite ore has been found, in bounding calculations, to severely retard the transport of neptunium-237 to the accessible environment. The calculations predict about half the improvement in repository performance as would be realized with the use of emplacement drift backfill. However, the bounding calculations assumed a sufficient amount of apatite under a waste package to retard all the neptunium-237, as well as any of the other actinides that may sorb to apatite, in a waste package. The actual amount of apatite needed and whether this amount is compatible with the need of the drift invert to structurally support the waste package has not been determined.

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- Tightly packing (line loading) the waste packages and backfilling after 100 years would result in a 50 percent probability of not exceeding a 0.1 mrem/yr dose rate at Amargosa Valley. There is, however, still significant uncertainty in whether the spent fuel cladding or drift wall temperature thermal goals would be violated in this scenario.

Table 4-3 summarizes these performance results in the context of the interim postclosure standard and two potential alternative standards. The capillary barrier, drip shield, and chemically treated backfill alternatives were not included in the table because, as discussed earlier, they are not considered feasible for enhancing engineered barrier system performance. The line loading concept was also not included in the table because of the significant unresolved thermal uncertainties associated with it.

The additional repository costs (relative to those costs found in the MGDS Advanced Conceptual Design Report) associated with backfilling of emplacement drifts include both the cost of constructing larger (5.5 m rather than 5.0 m diameter) emplacement drifts and the cost of emplacing the backfill over the waste packages. The additional repository costs amount to approximately \$461 million, which is about 25 percent of the current estimates for repository construction costs (about \$1.8 billion). Of this amount, \$116 million is from construction of the larger emplacement drifts and the remainder (\$345 million) results from emplacing the backfill.

The additional repository costs associated with a chemically conditioned invert, using a layer of phosphate containing sedimentary apatite ore, would range from \$20 million for a 200 mm thick layer to about \$330 million for a 1200 mm thick layer.

The testing and analysis costs associated with confirming the potentially available margin from galvanic protection or cladding performance have not been estimated.

Study Conclusions

Predictions of long-term repository performance (based on the advanced conceptual design engineered barrier system design and assumptions about site characteristics current at the time the study was developed) indicate that there would be significant margin to the interim postclosure standard limits out to 10,000 years. Performance is also estimated to be acceptable well beyond 10,000 years, although the performance margin would be significantly reduced for periods in the very distant future if no additional barriers or performance credits are applied. That is, there would be a 50 percent probability of not exceeding 10 mrem/yr over a one million year period, compared against the 10,000 year interim postclosure standard limit of 15 mrem/yr; and there would be a 99 percent probability of not exceeding a dose rate of 150 mrem/yr when calculated for one million years.

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Table 4-3. Quantitative Assessment of Compliance With Alternative Postclosure Performance Standards (mrem/year)

Standard peak/dose percentile/release point	Time frame (years)	Engineered Barrier System Performance Options ^a				
		ACD Reference	Galvanic Protection ^b	Cladding ^b	Backfill	Chemically treated invert ^b
Interim Postclosure Standard	10,000	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
15 mrem/50%/Amargosa-30 km	1,000,000	10	0.6	0.3	0.6	2
Hypothetical alternative postclosure standard	10,000	0.02	1×10^{-4}	1×10^{-4}	NA (<0.02)	NA (<0.02)
15 mrem/50%/5 km	1,000,000	200	NA (<200)	4×10^{-3}	18	NA (<200)
Hypothetical alternative postclosure standard	10,000	0.003	1×10^{-4}	2×10^{-3}	NA (<0.003)	NA (<0.003)
15 mrem/90%/Amargosa-30 km	1,000,000	30	2	0.8	2	NA (<30)

^aShaded areas indicate performance objective not met.

^bDoes not reflect conservative estimate of two-fold degradation in performance due to emplacement drift rockfall. (NA = Quantitative assessment not available; numbers below NA are bounding estimates.)

^cACD = advanced conceptual design

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There are a number of uncertainties pertinent to the required and/or potential contribution of the engineered barrier system to long term performance. These uncertainties include:

- Uncertainties about the nature of the long-term performance standard.
- Uncertainties in the Project's understanding of significant site parameters (e.g., water flux at the repository horizon, and the timing and impacts of postclosure emplacement drift rockfall).
- Uncertainty as to the level of confidence in the performance obtainable with the enhancements. Factors contributing to these uncertainties include: variations in thermohydrologic properties of backfill materials; long-term settlement of backfill and its impact on the performance of the backfill; uncertainty in the ability of the backfill material to evaporate water; offset in backfill performance caused by microbially influenced corrosion; and, in the case of the chemically treated invert, the amount of phosphate needed under a waste package.
- Uncertainty as to the general validity of the process models and abstractions used in the unqualified performance assessment codes, especially for analyses of performance over very long time frames. These uncertainties are large enough that study results pertinent to very long time frames should be viewed as indicators of performance trends more than as accurate predictors of repository performance.

These uncertainties must be considered in developing a recommendation regarding engineered barrier system performance requirements. As the Project's understanding of site characteristics continues to evolve, the results of the study will be reconsidered if appropriate.

The following recommendations were made considering the uncertainties associated with performance, the small margins available with current concepts against the potential long term standard, the potential for significant total system performance improvements with engineered barrier system performance enhancements, and the costs associated with those improvements.

1. Repository and engineered barrier system requirements should be modified to clearly reflect that there is no requirement to design or install backfill or its related emplacement systems, nor is there any requirement to design chemically conditioned inverts, drip shields, or other engineered barrier system performance enhancements.
2. A design requirement should be levied on the underground repository layout to provide a sufficient envelope such that a reasonable backfill emplacement system could be designed and added at a later date. As a contingency, adherence to this requirement should be demonstrated at the time of the viability assessment through an analysis of the emplacement drift design coupled with minimal development of a backfill system concept.

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3. As part of the overall license strategy, a regulatory compliance strategy should be adopted for the issue of engineered barrier enhancements at the time of the viability assessment. This strategy should (a) take advantage of the predicted performance of the repository being compliant with established limits, (b) acknowledge the small calculated margin to the limits, (c) acknowledge the uncertainties in the performance models, and (d) identify contingency activities that need to be performed to better quantify the performance benefits of the engineered barrier system enhancements (e.g., activities related to microbial-influenced corrosion, thermohydrologic value of backfill, and feasibility of chemically conditioned invert). The strategy should also take advantage of a long-term performance confirmation program for monitoring the need for an additional engineered barrier system performance barrier and the ability to backfit the repository with backfill (for example) if additional performance margin is required. This issue could be monitored and tracked as a potential license condition to be resolved during the performance confirmation period after repository operations have commenced.

Forecast: System studies planned for FY 1997 that may be related to the strategy for containment enhancement include the waste isolation requirements study and the waste package size study.

4.1.20 Design Activity 1.11.6.5 - Reference Calculations

The objective of this design activity is to provide a set of calculations that documents predictions of postclosure thermal and thermomechanical response of the host rock. These calculations may be used to address performance assessment issues. Thermal and thermomechanical response analyses performed to satisfy this design activity can be divided into near-field and far-field analyses; the near-field analyses can be further divided into container-scale analyses and drift-scale analyses.

Analysis of jointed rock performed for and discussed in the Engineered Barrier System Performance Requirements System Study included examination of emplacement drift stability using discrete block elements. This analysis shows that zones of rock block loosening and fallout that may develop following loss of ground support during postclosure could extend 3 m above the crown before stabilizing. In addition, joint movements too small to affect block loosening or overall stability could potentially extend as much as 10 m above and below the drift. However, this analysis indicates that block loosening and extension of joint movements do not affect the integrity of pillars between drifts and do not lead to ground surface subsidence behavior.

As-built geologic maps and tabulations of rock quality and rock joint data from portions of the ESF north ramp, main drift, and alcoves were also produced this reporting period. This data will be analyzed and will become part of a baseline data base to be used for analysis of the postclosure repository.

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Forecast: Near-field thermal and thermomechanical analysis of drift temperature and stability will continue as part of an ongoing task during FY 1997 and as repository design continues to evolve. In particular, jointed rock models will be used to examine the effects of long-term thermal and seismic load cases and to provide a basis for assessing postclosure drift behavior. The development of ESF as-built drawings and a baseline data base will continue during FY 1997. Use of this information in repository design is expected to begin during FY 1997.

4.1.21 Design Activity 1.11.7.1 - Reference Postclosure Repository Design

The objective of this design activity is to establish the information that will constitute the reference postclosure design for use in performance assessment and to document this information in the MGDS Advanced Conceptual Design Report (now complete) and in reports pertinent to the viability assessment and license application design.

The information needed for performance assessment is being continually developed as design and performance assessment progress.

A list of information needed for performance assessment of postclosure repository design was provided in Progress Report #14 (DOE, 1996b). Progress related to items on the list is described in other sections of the report: the most significant progress this reporting period is the elimination of the lower repository block from repository design (see Section 4.1.6 of this progress report) and the preliminary conclusion that backfill is not required in emplacement drifts for long-term performance (see Sections 4.1.8 and 4.1.9 of this progress report).

Forecast: The information needed for performance assessment is being developed and most should be available by March 1997 for use in performance assessment to support the viability assessment.

4.1.22 Design Activity 1.11.7.2 - Documentation of Compliance

The objective of this design activity is to document that the characteristics and configurations of the repository and engineered barrier systems have been adequately established to show compliance with both the postclosure design criteria of 10 CFR 60.133 and regulatory performance objectives. This compliance is to be demonstrated in the Advanced Conceptual Design Report and in documentation for license application design. This activity draws from the results of many other activities.

The MGDS Advanced Conceptual Design Report, completed last reporting period, documented how the repository and engineered barrier system concepts would be expected to meet the design criteria of 10 CFR 60.133 and the repository postclosure performance objectives. This demonstration, by the nature of conceptual design, was preliminary. As the design matures, the compliance demonstration will also mature. The license application design developed to

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support application for a construction permit will contain a more refined and complete compliance demonstration.

Progress Report #14 described how 10 CFR 60.133 requirements would be met, as described in the Advanced Conceptual Design Report. Only updates to those descriptions are included here. The 10 CFR 60.133 references are given, but the requirements are not quoted.

10 CFR 60.133(a) General criteria for the underground facility (1): The engineered barriers that would be part of the underground facility contribute to containment and isolation of radionuclides. Backfill in emplacement drifts, which is part of the engineered barriers, may be used if deemed necessary to help retard water flow to, and radionuclide egress from, the degraded waste packages. However, the backfill study (CRWMS M&O, 1996s) indicates adequate postclosure performance is obtained without backfill in emplacement drifts (see Section 4.1.8 of this progress report).

10 CFR 60.133(b) Flexibility of design: For waste emplacement at or greater than 83 MTU/acre, sufficient emplacement drifts can be developed within the upper repository block to allow emplacement of 70 000 MTU (see Section 4.1.8 of this progress report). The entire lower repository block is now available for contingency use; for example, if a lower thermal load is required or chosen, or if ground conditions in certain repository locations are unsuitable for waste emplacement. Additional emplacement area may also be available immediately north of the present upper repository block.

Compliance of the design with repository performance objectives as referenced in 10 CFR 60.133 is discussed in Chapter 6 of this progress report.

Forecast: Demonstration of compliance of the repository and engineered barrier designs with 10 CFR Part 60 will be refined as the designs are further developed in an ongoing process. This section of future progress reports will provide updates on the compliance demonstration as new reports and analyses become available.

4.2 REPOSITORY DESIGN CRITERIA FOR RADIOLOGICAL SAFETY (SCP 8.3.2.3)

Design Activity 2.7.1.1, discussed in Section 4.2.1 of this progress report provides the status of work performed to evaluate repository safety design criteria and performance goals. Radiological safety analysis is an ongoing process throughout all design phases of the repository project.

During this reporting period, a list of events was developed for consideration as design basis events. The list was further refined and formalized from the preliminary list provided in Progress Report #14 (DOE, 1996b) and was published in the Preliminary MGDS Hazards Analysis (CRWMS M&O, 1996u). The list was developed and documented in accordance with applicable QA procedures. In addition, pilot analyses were performed for a nonmechanistic

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waste package failure in the subsurface and for selected surface events. The pilot analyses were performed to develop a model for future consequence analyses, to identify potential issues, and to develop consistency within the various analyses to be produced within the multidisciplinary design basis event task team. To support these and future analyses, a source term analysis was developed. Additionally, significant efforts have been devoted to prioritizing event analyses to support viability assessment design and system description document development.

The next phase of this work involves reviewing the potential design basis events, identifying the analyses required to address each event, and scheduling the analyses in a manner that supports the viability assessment and the license application. This effort will develop into the final design basis event analyses that will be used to substantiate the radiological safety basis of the preclosure repository, as part of the viability assessment and repository license application. Those repository structures, systems, and components that help prevent or mitigate radiological releases in one or more design basis events will be subsequently classified as Important to Radiological Safety. Depending upon the role of the structures, systems, and components in a given event, design criteria and/or operational parameters will be imposed using the graded approach to establish QA controls.

4.2.1 Design Activity 2.7.1.1 - Design Evaluation for Compliance with Radiological Safety Design Criteria and Performance Goals

The objective of this design activity is to evaluate the repository design against the radiological safety design criteria and performance goals at each phase of the design and to provide feedback to the designers on needed corrections or modifications. This activity will result in a repository design that will protect repository workers and the public from radiological hazards during the preclosure period.

A preliminary hazards list and subsequent preliminary screening were discussed in Progress Report #14 (DOE, 1996b). During this reporting period, the formalization and QA documentation of the design basis event process began. A Preliminary MGDS Hazards Analysis (CRWMS M&O, 1996u) which is the formalization in accordance with QA procedures of the preliminary hazards analysis referenced in Progress Report #14, identified hazards with potential radiological consequences. These hazards represent potential initiating events and design basis event scenarios for surface and subsurface repository operations. As a result of this analysis, 30 external events were determined "not applicable" to the preclosure phase of a repository sited at Yucca Mountain and therefore do not require additional evaluation. These events are listed in Table 4-4.

In addition, the analysis identified 22 external events (Table 4-5) that warrant additional analyses to determine their potential applicability to a preclosure repository at Yucca Mountain. Some events may require only a frequency determination analysis to demonstrate the events are incredible at Yucca Mountain, while other events may be bounded by other events or precluded by design considerations.

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Table 4-4. External Events Excluded from Evaluation for Preclosure
Repository as per Preliminary Mined Geologic Disposal
System Hazards Analysis

Aquatic waves	Orogenic diastrophism
Avalanche	Pipeline accident
Coastal erosion	Sedimentation
Dam failure	Seiche
Denudation	Seismic activity, uplifting (tectonic)
Epeirogenic displacement	Stream erosion
Erosion	Subsidence
Glacial erosion	Tsunami
Glaciation	Undetected past intrusion
High lake level	Undetected geologic features
High tide	Undetected geologic processes
High river stage	Volcanic eruption
Hurricane	Volcanism, magmatic activity, extrusive and intrusive
Low lake level	Volcanism, ash flow
Low river level	
Meteorite impact	

Table 4-5. External Events Requiring Additional Analyses

Aircraft crash	Lightning
Debris avalanching	Loss of offsite/onsite power
Dissolution	Military activity-induced accident
Extreme wind	Rainstorm
Extreme weather fluctuations	Sandstorm
Fire (range)	Seismic activity, earthquake
Flooding (storm, river, diversion)	Seismic activity, subsurface fault displacement
Inadvertent future intrusions (man- made)	Seismic activity, surface fault displacement
Industrial activity-induced accident	Static fracturing
Intentional future intrusion (man- made)	Tornado
Landslide	Volcanism, ash fall

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A third group of 60 internal events were identified in the Preliminary MGDS Hazards Analysis by synthesizing subsurface and surface system functional areas of design and potential interactions that could impact a radiological waste form (e.g., disposal container, waste package, fuel assembly, radioactive waste processing system component). This list of events was generated by determining the applicability of internal generic events that could potentially interact with the waste form and result in a radiological release. The list of internal events has not yet been "reduced" into a smaller set of bounding events. Such a reduction will require, either individually or in combination with other events:

- A frequency analysis that demonstrates the event is incredible
- An analysis that demonstrates a release does not occur as a result of the event
- Some combination of the previous two analyses.

For each design basis event, a consequence analysis will be performed that demonstrates that the radiological consequences of the event are within regulatory requirements, or that identifies preventive or mitigating structures, systems, and components required to ensure the radiological consequences are within regulatory requirements;

"Source Terms for Design Basis Event Analyses," (CRWMS M&O, 1996v) which is currently in the review process, documents a review of isotopic inventories of pressurized- and boiling-water reactor fuel assemblies and high-level waste canisters. From this review source terms were determined for potential releases from pressurized-water reactor and boiling-water reactor fuels, and high-level waste canisters. The source terms, expressed in terms of rem per unit waste form (e.g., per fuel assembly) for each organ, are intended for use in radiological consequence analyses. These results are used as inputs to the pilot and other design basis event consequence analyses (as described in the following paragraphs).

Two pilot analyses, one for surface and one for subsurface, are being performed to evaluate the environmental consequences of selected potential design basis events. The pilot analyses will establish the dose model and assumptions that will be used for subsequent radiological consequence analyses (i.e., for other events) and will serve as a basic template for these subsequent analyses.

As the first in a series of design basis event-related consequence analyses, these pilot analyses are also the first to incorporate revised radiological safety criteria from the NRC's proposed revision to 10 CFR Part 60 on design basis events (ref. 60 FR 15180, commonly called the "design basis event rule change"). These revised criteria are being used by the design basis event task team, because approval and release of this revision are considered imminent. (Use of these limits will be controlled in these analyses [i.e., marked as "To be verified" as appropriate] pending formal release of the revision.)

There are two categories of design basis events, each having different dose consequence acceptance criteria. Because Category 1 design basis events are reasonably likely to occur at

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least once in the preclosure lifetime of the facility, the dose criteria correspond to the normal operating limits of 10 CFR Part 20. For the more unlikely Category 2, the dose criterion is 5 rem at the site boundary. The categorization of design basis events also affects the dose model and assumptions used for radiological consequence analyses.

Forecast: The development of design basis event analyses in accordance with appropriate QA procedures will continue. These analyses are the formal documentation of the design basis event process. The analyses are scheduled to support the viability assessment and the license application.

4.3 NONRADIOLOGICAL HEALTH AND SAFETY (SCP SECTION 8.3.2.4)

This section describes work performed to address nonradiological health and safety issues and concerns. Discussions of general work concerning this topic follow. Design Activities 8.3.2.4.1.1 and 8.3.2.4.1.2, discussed respectively in Sections 4.3.1 and 4.3.2 of this progress report, provide the status of work performed to evaluate repository design against certain nonradiological safety design criteria and performance goals discussed in the SCP (DOE, 1988).

Because the safety and health of workers receives high priority in repository design, the objective of this design activity is to evaluate the repository design against the nonradiological safety design requirements, criteria, and performance goals at each phase of the design and to provide feedback to the designers on needed corrections or modifications.

Accomplishments during this reporting period focused on the Preliminary Hazards Analysis (CRWMS M&O, 1996u) completed in September 1996, as discussed in Section 4.2.1. Completion of this analysis supports the revision of the Preliminary System Safety Analysis for the Advanced Conceptual Design during FY 1997 in conjunction with design evolution.

Forecast: A revised analysis is planned for FY 1997. Included are revisions to the scenarios as shown in the Preliminary Systems Safety Analysis for the advanced conceptual design. The radiological scenarios will no longer be included in the Preliminary Systems Safety Analysis because they are now included in the Preliminary MGDS Hazards Analysis (CRWMS M&O, 1996u) and subsequent Design Basis Event Analyses. The nonradiological scenarios will be limited to design applications that are unique or unusual and that may pose new hazards. Typical well-established operations and the associated equipment will be reviewed but not analyzed if they clearly operate under well-established standard conditions. This approach is similar to the approach taken for Job Safety Analyses which will be used as a precedent.

4.3.1 Design Activity 8.3.2.4.1.1 - Design Activity to Verify Access and Drift Usability

The methods used to develop the conceptual design of the repository were based on preliminary data. The ESF offers an opportunity to verify these design activities and to

substantiate or provide the basis for adjusting the design techniques used. The objective of this specific activity is to verify the design techniques used to develop the conceptual design of the repository and to determine the suitability of the ESF access ramps and drifts for repository use.

No specific work was performed in this design activity during this reporting period. However, tunneling in the ESF north ramp and main drift has, over the last several reporting periods, demonstrated the viability of the tunnel boring machine as the primary means of excavating the repository openings. The current repository layout design incorporates the north ramp, main drift, and south ramp; and the balance of the repository perimeter and access drifts will be similar in design and construction.

With maintenance, the ESF ground support is expected to serve for the interim caretaker period between completion of the ESF construction and start of repository construction. During repository construction, the ESF ground support will be upgraded as necessary to repository standards as construction advances. The ESF utilities (compressed air, water, and power), conveyor, rail haulage, and ventilation system, appear suitable with some modifications for repository development (construction). For repository emplacement operations, the Project plans to remove the ESF and repository construction systems and to replace them with applicable repository systems. Design of these systems is still at the conceptual stage.

As design progresses for repository development and emplacement, both the criteria and data needs for repository systems will become more clearly defined. Design criteria being developed for the repository tunnels, including the ESF openings, address requirements such as the purpose of the opening (for example, access route for the waste package transporter), and the required functional life of the opening. Repository design also includes critical assessment of the ESF design and construction experience and of the design verification data. Maintenance and long-term upgrading of ESF systems, such as ground support, will be based to a large extent on data from construction and operational experience, ongoing performance confirmation testing, and where applicable, repository needs.

Data from the planned heater test area and ground support performance confirmation testing will provide input for the design of the emplacement drift ground supports. The emplacement drift ground support design will address thermal loading resulting from waste package heat and the need for minimal maintenance over the caretaker and retrieval periods. Because maintenance will be difficult and costly once waste has been emplaced, liner systems such as concrete segments that could be installed behind the tunnel boring machine are being considered for these drifts.

Forecast: As repository design advances, repository data needs will become better identified, and design verification activities will be modified accordingly. Data gathered from the ESF Title II design verification activities during ESF construction and testing will be used as input for developing the repository design during FY 1997 and future years and to substantiate assumptions identified in the Controlled Design Assumptions Document (CRWMS M&O, 1996e).

4.3.2 Design Activity 8.3.2.4.1.2 - Design Activity to Verify Air Quality and Ventilation

The objective of this activity is to assess the impact of site characteristics on the repository ventilation design to ensure a safe working environment (temperature, humidity, velocity and composition of air). Site characteristics will determine dust quantities produced during construction, in situ gas types and quantities, and the wall roughness required for ventilation flow calculations. Data gathered from construction monitoring and site characterization will be used as input for repository ventilation design.

Air quality in a confined space (subsurface repository) may vary significantly with the amount (flow rate or quantity) of air provided to the area being ventilated. Therefore, the study of air quantity is also an important activity for the design of the repository ventilation system.

Ventilation survey activities were conducted for the current ESF ventilation system operation to determine the ESF airway resistance factors, the airflow rates and air pressures were measured at selected locations in the ventilation duct and the ESF drift. Preliminary analysis of the field airflow data was also performed. The airway resistance factor for the ESF ventilation duct was established and will be used in applicable parts of the repository ventilation design.

Data on dust concentrations were obtained from the ongoing monitoring of the ventilation system supporting the current tunneling practices. The data are being evaluated to determine the relationship of airflow and airborne dust generated during the tunnel excavation, ventilation leakage, specific minerals present in the rock, conveyor haulage, and other factors. This will result in requirements for air quantity to maintain an acceptable air quality level and will lead to better ventilation arrangement alternatives to meet the repository subsurface environmental requirements.

Forecast: Additional ventilation data will be collected. Further evaluations of appropriate air quantity needs and airflow arrangement for the repository ventilation will be conducted. This information will be provided to repository design in FY 1997 as an input to repository design that will support the viability assessment.

4.4 PRECLOSURE DESIGN AND TECHNICAL FEASIBILITY (SCP SECTION 8.3.2.5)

4.4.1 Design Activity 4.4.3.1 - Operations Plan to Accompany the Advanced Conceptual Design

The objective of this design activity is to produce an operations plan to accompany the advanced conceptual design. A plan is needed to effectively design and evaluate the preclosure performance of the potential repository.

As reported in Progress Report #14, the advanced conceptual design has been completed, and therefore, this activity has been closed.

Forecast: This activity is closed.

4.4.2 Design Activity 4.4.3.2 - Operations Plan to Accompany the License Application Design

The objective of this design activity is to produce an operations plan to accompany the license application design. A plan is needed to effectively design and evaluate the preclosure performance of the potential repository.

Under the current plans and schedules, license application design is not scheduled to begin until FY 1998. Because advanced conceptual design is complete, work performed before FY 1998 in developing a repository operations plan for viability assessment will be reported under this design activity.

High-level operations descriptions that reflect repository design development were recently published in the MGDS Concept of Operations (CRWMS M&O, 1996w). Previously, the MGDS concept of operations was provided in Section 5 of the Controlled Design Assumptions Document (CRWMS M&O, 1996e). The newly published concept of operations was modified from the version published in the Controlled Design Assumptions Document to accomplish the following:

- Reflect the design evolution through advanced conceptual design, including expanded detail and better alignment with the design description in the MGDS Advanced Conceptual Design report.
- Reflect the recent update of the CRWMS Total System Description (CRWMS M&O, 1996x), including the introduction of Regional Servicing Agents, an option for an Interim Storage Facility, the requirement to dispose of DOE-owned spent nuclear fuel in the repository, and the shift away from using disposable commercial spent nuclear fuel canisters (e.g., multi-purpose canisters). (A Regional Servicing Agent is an organization that would be responsible, within its region of the country, for all activities and services needed to accept and transport commercial spent nuclear fuel.)
- Incorporate design changes that have occurred since completion of the advanced conceptual design, including a change to eliminate the capability to add filler material to spent fuel canisters and the introduction of performance confirmation concepts.

Forecast: The viability assessment design effort will continue, and additional operations concepts will be developed. The operations descriptions will be provided in the System Design Descriptions, which are expected to be issued in the second half of FY 1997. The concept of operations may be updated in the next reporting period to reflect early design evolution.

4.4.3 Design Activity 4.4.4.1 - Repository Design Requirements for License Application Design

The objective of this design activity is to develop repository design requirements for license application design.

The Repository Design Requirements Document (DOE, 1994f) captured the initial set of design requirements to support the development of license application design. The status of the revision to the Repository Design Requirements Document is provided in Appendix B of this progress report.

Forecast: The updating of repository design requirements for license application design is in abeyance pending resolution of the document hierarchy, which is discussed in Section 2.1.3 of this progress report.

4.5 SEAL CHARACTERISTICS (SCP SECTION 8.3.3.2)

4.5.1 Study 1.12.2.1 - Seal Material Properties Development

The ability to seal openings to and inside a repository could significantly impact postclosure repository performance. The Yucca Mountain sealing program concentrates on cementitious and earthen materials emplaced in shafts, ramps, and boreholes. The strategy for sealing the proposed repository is to place seals in the shafts, ramps, and boreholes so that they do not act as potential pathways for water and gas flow. Current efforts are focused on in situ and laboratory testing and analysis of cementitious seal components planned for use in sealing exploratory boreholes at Yucca Mountain. Potential sealing locations include nonwelded Topopah Spring Tuff and the Calico Hills Formation.

An issue of importance for sealing is the longevity and durability of emplaced seals, particularly seal materials. Seal performance for all potential seal locations is related to initial performance (including the effect of emplacement techniques), as well as to long-term performance (mechanical/hydrologic/geochemical stability).

Study Plan 8.3.3.2.1, "Seal Material Properties Development," was completed and accepted by DOE this reporting period. This study plan outlines the seal material testing and analysis needed to evaluate and predict seal performance in situ, including longevity of selected materials. Seal materials currently being evaluated include Portland-based cements as well as crushed tuff and clays.

Activity 1.12.2.1.1- Detailed property determination of cementitious-based and earthen materials. Activity 1.12.2.1.1 concerns the determination of detailed properties of cementitious and earthen materials. The objective of this activity is to conduct laboratory testing and analysis to determine material properties for seals.

No progress was made on this activity during the reporting period.

Forecast: Future testing and analysis will continue to focus on evaluating the performance of cementitious seals emplaced in thick-walled cylinders of tuff. Additional durability tests conducted under accelerated and extreme environmental conditions are also planned. Resumption of this work awaits funding. The schedule and need for future work in this area will depend on the results of the seals systems study to be performed in FY 1997. (See the forecast for Section 4.5.5 of this progress report.)

Activity 1.12.2.1.2 - Hydraulic conductivity and consolidation testing of crushed tuff. This activity concerns establishing the hydraulic conductivity and consolidation behavior of crushed tuff to support the development of criteria for shaft fill and drift backfill.

No progress was made on this activity during the reporting period.

Forecast: No activity is planned for FY 1997. The schedule and need for future work in this area to support decisions on sealing and backfill will depend on the results of the seals systems study to be performed in FY 1997. (See the forecast for Section 4.5.5 of this progress report.)

4.5.2 Design Activity 1.12.2.2 - A Degradation Model for Cementitious Materials Emplaced in a Tuffaceous Environment

The objective of this activity is to develop a degradation model that will provide insight into how material properties of sealing components, especially permeability and strength, could be altered after being in contact with tuff.

No progress was made on this activity during the reporting period.

Forecast: No activity is planned for FY 1997. The schedule and need for future work in this area to support decisions on sealing will depend on the results of the seals systems study to be performed in FY 1997. (See the forecast for Section 4.5.5 of this progress report.)

4.5.3 Study 1.12.2.3 - In Situ Testing of Seal Components

The objective of this study is to conduct in situ testing and analysis to evaluate the behavior of selected sealing components under both realistic in situ conditions and under unlikely conditions.

Study Plan 8.3.3.2.2.3, Study Plan for In Situ Testing of Seal Components was completed and accepted by DOE this reporting period. This study plan is based on the seal testing and analysis strategy described in Fernandez et al. (1993).

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Forecast: Resumption of work on planning for in situ small-scale borehole tests will depend on the results of the seals systems study to be performed in FY 1997. (See the forecast for Section 4.5.5 of this progress report.)

4.5.4 Design Activity 1.12.4.1 - Development of the Advanced Conceptual Design for Sealing

The objective of this activity is to provide the conceptual seal design for the repository. However, as reported in Progress Report #14, advanced conceptual design has been completed, and therefore, this activity has been closed, and all further work will be reported under Design Activity 1.12.4.2.

Forecast: This activity is closed.

4.5.5 Design Activity 1.12.4.2 - Development of the License Application Design for Sealing

Design Subactivity 1.12.4.2.1 - Define subsystem design requirements. The objective of this design subactivity is to refine design requirements that will assist in the development of sealing components for the license application design.

No progress was made during the reporting period. These design requirements are expected to be defined by the start of license application design and will be factored into that design.

Design Subactivity 1.12.4.2.2 - Perform trade-off studies to support license application design development. The objective of this design subactivity is to provide technical justification for the selection of the final seal designs.

No progress was made during the reporting period. This activity will be addressed in time to support license application design.

Design Subactivity 1.12.4.2.3 - Develop license application design for seals. The objective of this design subactivity is to provide the license application design for seals.

No progress was made during the reporting period. This activity will be addressed in time to support license application design.

Forecast: A systems study is planned for FY 1997 to address requirements for sealing the repository shafts, ramps, and boreholes. Boreholes needing sealing may have resulted from surface-based testing or subsurface testing. Specifically, the study will develop requirements for seals, and determine the role the seals must play in establishing compliance with 10 CFR Part 60 with respect to waste isolation and to returning the site back to its natural condition. The study also will determine the approach for meeting state and county regulations related to abandoned

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boreholes and the function the seals must play in meeting those requirements. The most recent work on seals was done several years ago, before total system performance assessment was developed, before a great deal of site data was collected, and before the advanced conceptual design was completed. This earlier work must be evaluated, and updated if necessary, in order to support the seal design activities.

CHAPTER 5 - WASTE PACKAGE

INTRODUCTION

The waste package consists of the waste form (spent nuclear fuel assemblies) or canistered waste form (canistered fuel or canisters of defense high-level waste glass), fill gas, and a disposal container. The fuel canister is an outgrowth of the former multi-purpose canister effort, and refers to canisters intended primarily to facilitate handling of the waste. Per 10 CFR 60.2, the waste package may also include shielding, packing, and other absorbent materials, but these materials have not been implemented in current designs.

The introductory discussion in Chapter 4 of this progress report, which describes the current focus of repository and waste package design, is applicable to waste package design but is not repeated in Chapter 5.

The waste package program includes (a) the development of waste package design bases, (b) development of a reference design, (c) analysis of design, testing and modeling of container materials, (d) testing and modeling of the waste form, and (e) working with other Yucca Mountain Site Characterization Project (Project) elements to characterize the waste package emplacement environment. This chapter describes progress in the waste package design and environment program. Waste package materials testing and modeling are described in Chapter 6.

Waste package design is an integrated program effort to develop a waste package that will meet performance objectives and design criteria for the potential repository. Among the more significant objectives are the following:

1. Waste package lifetime should be well in excess of 1000 years.
2. The waste package container must contribute to controlling the release rate of radionuclides during the period of isolation.
3. Criticality must be controlled during the period of regulatory concern.

The relationship between a favorable viability assessment and achievement of these objectives was discussed in Progress Report #14 (DOE, 1996b) and the Controlled Design Assumptions Document (CRWMS M&O, 1996e).

The following discussion summarizes some of the more notable waste package and engineered barrier system activities that occurred during this reporting period. More details are given in Sections 5.1 through 5.4.

In reading the text that follows, it should be recognized that the Project's understanding of site characteristics continues to evolve. For example, there are several indications that percolation flux may be considerably higher than was previously thought to be the case. Some of the studies and analyses discussed in this chapter assumed a lower percolation flux than the range

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of values supported by current information and analysis results. Therefore, the results of these studies will be re-evaluated as appropriate to address the evolving understanding of site characteristics.

Evolution of Waste Package Design

As systems strategies and long-term performance strategies have evolved, waste package designs have also evolved. Disposal container design is now focused on the following four basic types (as discussed in Section 5.1.1), all of which are robust, multibarrier, metallic designs:

1. Disposal container for uncanistered fuel assemblies
2. Disposal container for canistered fuel
3. Disposal container for defense high-level waste glass pour canisters
4. Disposal container for defense high-level waste glass pour canisters and U.S. Department of Energy (DOE)-owned spent fuel

The disposal containers for uncanistered fuel that are currently under consideration are similar to those developed during advanced conceptual design, but with significant changes to the internal structure. Two designs for uncanistered fuel are being analyzed, one with a capacity of 21 pressurized water reactor fuel assemblies and another with a capacity of 44 boiling water reactor fuel assemblies. Additional designs with smaller capacities may be necessary for fuel that is unusually reactive or has an unusually high heat output. The disposal container design for defense high-level waste glass is unchanged from that developed during advanced conceptual design. However, since the Project baseline has been extended to encompass DOE-owned spent nuclear fuel, a modified version of the disposal container for defense high-level waste glass is also being considered. The modified design is intended to accommodate DOE-owned spent fuel along with waste glass canisters. DOE-owned spent fuel includes defense and research reactor fuel, as well as fuel from certain demonstration reactors (e.g., Shippingport and Fort St. Vrain). The sizes and capacities of the disposal container designs for canistered fuel will be chosen to accommodate the canisters to be placed in them.

In previous reporting periods, most commercial spent fuel was assumed to be canistered at the reactor site. Fuel canisters would be sealed before shipping and normally not reopened at the repository. Emphasis has been shifted away from canistered fuel, however, because of the cancellation of the multi-purpose canister effort. Work during the reporting period, therefore, focused on the other types of containers. Unless there is renewed emphasis on canisters, the disposal container for canistered fuel will remain at the advanced conceptual design stage (i.e., with little or no further design development).

Figures 5-1 and 5-2, respectively, are cutaway schematic drawings of two disposal container designs that are under consideration. These designs are intended for spent nuclear fuel and for defense high-level waste glass plus DOE-owned spent fuel. Although the designs,

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Figure 5-1. Schematic of Disposal Container for Unclad Pressurized Water Reactor Spent Nuclear Fuel

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Figure 5-2. Schematic of Disposal Container for Defense High-Level Waste Glass and DOE-Owned Spent Nuclear Fuel

particularly that for uncanistered spent fuel, are superficially similar to those presented in Progress Report #14, they include significant changes.

There have been changes in the basket for the container design, shown in Figure 5-1, that would hold 21 uncanistered pressurized water fuel assemblies. In this design, the neutron-absorbing material is in the form of interlocking plates, which do not require welding. Carbon steel tubes contribute to conducting heat to the surface of the waste package. However, a different design with aluminum thermal shunts in the fuel basket may still be necessary for fuel with an unusually high heat output.

For the design shown in Figure 5-2 that would hold both waste glass and DOE-owned spent fuel, the capacity has been increased from four to five high-level waste glass canisters, and a gap in the center is proposed for disposal of DOE-owned spent nuclear fuel. A circular tube would be placed at the center of the disposal container, and a basket would be installed in the tube. The basket cells would hold DOE-owned spent nuclear fuel. The basket design may vary among waste packages, depending on the type of DOE spent fuel to be disposed of in a given waste package.

Materials Selection

For the spent nuclear fuel disposal containers, the materials under consideration for the containment barriers have changed. For both boiling water reactor fuel and pressurized water reactor fuel, the preferred material of the inner barrier has been changed to nickel-base alloy ASTM B 443 (Alloy 625). This material provides added corrosion resistance. The preferred material for the outer containment barrier is still carbon steel.

Like the disposal containers for spent nuclear fuel, those under consideration for defense high-level waste glass would also have an outer barrier of carbon steel and an inner barrier of ASTM B 443. Previous concerns about chemical interactions between carbon steel and the defense high-level waste have been resolved by the determination (CRWMS M&O, 1996h) that waste glass dissolution rate would have little effect on repository performance. This is because of the great reduction in radioactivity in high-level waste glass during the first 1000 years. Thus, little radioactivity would be left to be concerned about when waste packages are subsequently breached, exposing the glass to iron ions. Therefore, the performance advantage of a copper-nickel containment barrier does not justify its additional cost.

Design Analyses

Design analyses, discussed in Section 5.1.2, continue to focus on thermal, structural, and criticality analyses.

Thermal analyses have been performed to calculate temperature fields at the scale of one emplacement drift, to calculate temperature fields at the scale of one waste package, and to develop and test effective conductivity models for spent nuclear fuel assemblies. Also, because backfilling and waste package spacing both affect compliance with thermal goals; these

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relationships have been examined. In addition, effective thermal conductivities have been developed for various types of spent nuclear fuel assemblies. The use of an effective thermal conductivity allows the analyst to replace the complex structure of the fuel assembly with an equivalent homogeneous solid, which saves substantial computer time but has little effect on the accuracy of the results.

Structural analysis focused on the changes in the structural integrity of waste packages that occur as the containment barriers and baskets are degraded. Areas of investigation included resistance of the containment barriers to static loads, basket stability under static loading, barrier capability under rock impact loading, waste package capability during seismic events, spent nuclear fuel structural capabilities, and rock size required to cause a breach in containment barriers. The results of structural analyses were combined with those from a uniform corrosion model to predict how the waste packages will lose load-bearing capacity as a function of time. The analyses reflect a more realistic treatment of the propagation of failures through the containment barriers. As a result, the size of rock required to cause a containment failure is currently predicted to be substantially larger than previously predicted.

Analyses of internal criticality have been reported previously. This work was extended during this reporting period to encompass criticality external to the waste package and the consequences of such a criticality for commercial spent nuclear fuel. The general methodology for identifying and generating potentially critical configurations was refined to ensure that all representative configuration types are considered. The probability of an external criticality was found to be extremely small. Even if a criticality should occur, the power produced by the reaction would be limited to a few kilowatts, and the changes in radionuclide inventory would be small.

Production Technologies

Project understanding of production technologies for disposal containers advanced considerably as discussed in Section 5.4. A method that shows considerable promise is to form the outer corrosion allowance and inner corrosion resistant barriers separately, then use a shrink fit to hold them together. Because of equipment limitations, the containment barrier for this method could not be formed as one cylinder; instead two cylinders would be made and welded end to end. This method of fabrication promises significantly lower costs than those of producing the inner containment barrier as a welded cladding. However, it is not clear whether the method will provide sufficient electrical coupling between the two layers to ensure galvanic protection of the inner barrier by the outer.

Near-Field Studies

Understanding of near-field characteristics and behavior is essential to accurately predict waste package and repository postclosure performance. During this reporting period, the Project continued to improve its understanding of near-field thermal-hydrological-mechanical-chemical processes. In addition, laboratory and design work in support of important in situ thermal tests continued. Major accomplishments included the following:

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- Hydrothermal testing of vitric and tuffaceous rock under unsaturated conditions was completed as discussed in Section 5.2.2. Partial results available from analysis of the test data have helped confirm the expectation that alteration as a function of time in the rock is sensitive to temperature and extent of prior alteration. The results of this work will be an input into considerations regarding repository thermal loading.
- Sensitivity studies were performed as discussed in Section 5.2.3 to help establish the effect of various repository and waste package design parameters on predicted thermal-hydrological conditions. These conditions were found to be most sensitive to lineal mass loading, axial waste package spacing, and backfill thermal conductivity. The studies noted that increasing the lineal mass loading and decreasing the waste package axial spacing as compared with the advanced conceptual design would result in more uniform drift and waste package temperatures, liquid saturation in the rock, and liquid-phase flux along the drifts. This situation would be expected to reduce the likelihood of some waste packages seeing relatively severe corrosion conditions during the period in which waste decay heat significantly affects repository conditions. This benefit must be balanced against the increased potential for fuel cladding and drift wall temperature goals being exceeded because the waste packages would be so closely spaced. This issue is being evaluated to support selection of a waste package arrangement for use in the design to support the 1998 viability assessment. Higher percolation fluxes would significantly suppress the extent of rock dryout and humidity reduction and will be considered in ongoing studies.
- Results from geomechanical modeling and test activities are discussed in Section 5.2.4. During this reporting period, coupled three-dimensional modeling of thermal-mechanical-hydrological behavior of the proposed repository was initiated. The temperature distribution computed by the NUFT code, in a thermal-hydrological simulation, was passed to the FLAC code for computation of stress and deformation fields. The objective is to use this coupled model for near-field design simulations and for simulations of both the single heater test and the drift-scale test. Results from laboratory thermal-mechanical tests at elevated temperatures on 0.5-m scale blocks of Topopah Spring Tuff indicate that high temperatures may help to close and heal cracks, leading to a decrease in the permeability of tuff in the near field and potentially improving predicted repository performance.
- As discussed in Section 5.2.5, laboratory work continued in support of two Exploratory Studies Facility (ESF) thermal tests: a single-heater test and a drift-scale test. These two tests will be extremely important in characterizing the effects of waste decay heat on the repository near field. The single-heater test has begun, and the drift-scale test will begin in FY 1997. During this reporting period, laboratory work primarily involved (a) refining techniques for measuring conditions in the rock before, during, and after the tests and (b) characterizing conditions in rock samples subjected to various conditions representative of phenomena that could be expected to occur in the proposed repository. For example, x-ray imaging to determine water saturation in near-field rock

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revealed that fracture flow against a thermal gradient is slower than at room temperature. This result will be useful in repository performance assessments.

Near-field work in FY 1997 will be focused on attaining better understanding of thermally driven coupled processes. Results of work performed in support of this objective will be used to directly support performance assessment and repository and waste package design. This work, which will be reported in FY 1997, will synthesize results from the following types of laboratory work:

- Laboratory measurements of rock properties undertaken to support ESF or other field-scale thermal tests, or to bound the results of modeling undertaken to support design, system studies, or performance assessment
- Experiments performed to assist in the analysis or interpretation of field-scale thermal tests of phenomena such as the creation of refluxing zones in fractures, fracture healing, and mineral alteration
- Laboratory-scale tests of multiply coupled processes (e.g., thermal-hydrological-mechanical-chemical)
- Property measurements providing direct input to performance assessment, such as radionuclide solubilities and sorption coefficients of engineered barrier materials
- Laboratory tests needed to confirm or test models, using samples obtained in the ESF or from the surface as appropriate.

In addition, preparations for the large block test, deferred for FY 1996 because of funding constraints, will resume in FY 1997. This test will significantly enhance the Project's confidence in its ability to predict postclosure thermal-hydrological conditions in the near field.

5.1 WASTE PACKAGE DESIGN (SCP SECTION 8.3.4.2)

5.1.1 Design Activity 1.10.2.1 - Waste Package Design Development

The purpose of this activity is to develop waste package designs. This activity includes the development of conceptual designs, from which one or more concepts will be chosen for further development. Also included is the development of more detailed designs to support activities such as license application design.

Subactivity 1.10.2.1.1 - Disposal container design. The purpose of this subactivity is to develop design concepts for the disposal container itself, as opposed to the waste form that will be a part of the waste package.

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Disposal container design is now focused on the following four basic container types, all of which are robust, multibarrier, metallic designs:

1. Disposal container for uncanistered fuel assemblies
2. Disposal container for canistered fuel
3. Disposal container for defense high-level waste glass pour canisters
4. Disposal container for defense high-level waste glass pour canisters and DOE-owned spent fuel

The disposal container designs, including those for defense high-level waste, are intended to be of similar dimensions for handling and emplacement efficiencies and convenience. Project emphasis has been shifted away from canistered fuel because of cancellation of the multi-purpose canister effort. Accordingly, there will be little analysis and further design development of disposal containers for canistered fuel unless there is renewed emphasis on this concept.

Disposal Container for Uncanistered Pressurized Water Reactor Fuel

In the design concept currently under consideration, uncanistered fuel assemblies would be individually placed in the disposal container at the repository, and the two disposal container closure lids welded into place. The containment barriers would consist of an outer layer of carbon steel and an inner layer of ASTM B 443 (nickel-base Alloy 625). Plates of stainless steel-boron alloys used in the basket construction would provide criticality control, heat conduction, and structural support. The basket would be supported by basket guides of carbon steel that would be welded to the inner containment barrier. The square openings in the basket would be lined with carbon steel tubes, which would provide an additional path for conducting heat from the fuel to the surface of the waste container.

Disposal Container for Uncanistered Boiling Water Reactor Fuel

Materials and construction for this disposal container would generally be similar to those of the disposal container for pressurized water reactor fuel. The openings in the basket would be smaller because of the smaller cross section of a boiling water reactor assembly. Because of their lower heat output, boiling water reactor assemblies do not require basket tubes.

Disposal Container for Defense High-Level Waste Glass Plus DOE-Owned Spent Fuel

This disposal container is commonly referred to a "defense high-level waste glass disposal container," but a new design is being considered to accommodate both defense high-level waste and DOE-owned spent fuel. During advanced conceptual design, the disposal container for defense high-level waste glass was designed to hold four canisters. An additional design under consideration would allow each disposal container to hold an additional canister. In the center of the disposal container would be a circular tube, and inside the tube would be a basket that would

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hold DOE-owned spent fuel. Five sealed pour canisters of high-level radioactive waste would be placed in a circle around the tube. Like the uncanistered fuel disposal containers, there would be a double containment barrier, again with an outer layer of carbon steel and an inner layer of ASTM B 443 (nickel-base Alloy 625). Previous concerns with chemical interaction between carbon steel and defense high-level waste have been resolved by the determination that dissolution rate of waste glass would have little effect on repository performance due to the substantial reduction in radioactivity present by the time waste packages would corrode enough to expose waste glass to iron ions.

Canistered Fuel Disposal Containers

Because of the reduced Project emphasis on canistered fuel, the advanced conceptual designs of disposal containers for canistered fuel will be retained without further analysis unless there is renewed emphasis on fuel canisters.

Subactivity 1.10.2.1.2 - Design basis fuel. The purpose of this subactivity is to determine the design basis spent fuel for use in waste package design.

A revised design basis fuel analysis, which was forecast in the previous progress report, was not completed this period because the supporting analyses have not been completed. The supporting analyses needed involve the calculation of waste package effective neutron multiplication factors for more burnup/enrichment pairs and improved parameterization of the neutron multiplication factor for an infinite medium for boiling water reactor fuel.

Forecast: The disposal container designs will be analyzed in detail during FY 1997 in support of the 1998 viability assessment. Few significant changes to the design are expected before the viability assessment. A revised design basis fuel will be determined and published upon completion of the supporting analyses. Revision of the analysis of internal criticality and the effects of basket degradation has been delayed but not canceled. Completion of the revision is expected in FY 1997.

5.1.2 Design Activity 1.10.2.2 - Design Tools

The purpose of this design activity is to develop, verify, and validate the computer design tools for waste package design.

Plans for verifying and validating new versions of the thermal and structural analysis tool ANSYS were revised. ANSYS version 5.2 was to have been verified and validated during the reporting period, but it was determined to be more cost effective to continue to use version 5.1, and then upgrade directly to version 5.3.

The neutronics computer code package MCNP 4A was verified and validated according to applicable procedures. Because of quality assurance questions, the earlier verification and validation of SCALE (Standardized Computer Analyses for Licensing Evaluation) version 4.2

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was revisited. SCALE version 4.2 has again been approved for quality-affecting work. Verification and validation of SCALE version 4.3 were delayed until the next reporting period.

Forecast: During FY 1997, SCALE will be upgraded to version 4.3. The thermal and structural analysis tool ANSYS will be upgraded to version 5.3. These computer design tools will support future design products such as those described in Section 5.1.3 of this progress report.

5.1.3 Design Activity 1.10.2.3 - Design Evaluations

The purpose of this activity is to produce evaluations of significant issues pertinent to successful waste package design.

Subactivity 1.10.2.3.1 - Thermal. The purpose of this subactivity is to perform analyses of thermal performance parameters that affect waste package design.

The thermal analyses reported in the previous progress report supported the resolution of issues for the reference Mined Geologic Disposal System (MGDS) design and were presented in the Mined Geologic Disposal System Advanced Conceptual Design Report (CRWMS M&O, 1996b). The work reported here represents extensions of or significant advances from that work for the waste package design effort. The activities completed provide needed groundwork in support of viability assessment and license application.

Thermal design efforts have advanced in three main areas: (1) evaluating the repository and emplacement drift thermal behavior and its impact upon waste packages, (2) evaluating waste package thermal conditions with regard to meeting the licensing requirements, and (3) benchmarking spent nuclear fuel effective conductivity models against experimental data to ensure that the peak cladding temperatures are predicted accurately for licensing requirements evaluations.

Emplacement-Scale Thermal Analyses

The first step in the thermal evaluation of the waste package is to determine the time-dependent response of the repository to the decay heat of the emplaced waste packages. This emplacement-scale evaluation must consider that the waste package both affects (through thermal loading) and is affected by the conditions of its near-field environment. Although a given thermal (mass) loading is typically characterized by a single number, such as 83 MTU/acre, the thermal response of the repository also depends on the characteristics of the waste stream such as spent fuel age, receipt rates, delivery scenarios (youngest-fuel-first versus oldest-fuel-first), waste package size, emplacement spacing, and design basis fuel.

Emplacement-scale evaluations were performed to support systems studies considering both emplacement drift backfill and thermal loading and to advance the waste package design effort. The results of evaluations considering a single waste package [presented in the

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Engineered Barrier System Performance Requirements Systems Study Report (CRWMS M&O, 1996s)] (discussed in more detail in Section 4.1.19) indicate waste package and drift wall temperatures depend in large part on the assumptions used to estimate the average waste stream heat loads and the variability in heat loads within the waste stream. Changes in waste receipt (from youngest-fuel-first to oldest-fuel-first) resulted in 10°C lower peak temperatures, and packages for pressurized water reactor fuel generally resulted in the highest near-field temperatures. Changes in drift geometry were less important. An analysis of emplacement drift backfill indicated that backfill with an effective thermal conductivity greater than 0.4 to 0.5 W/m·K can be emplaced 100 years after waste package emplacement without violating the thermal goal for spent nuclear fuel cladding. This result shows that it is practical from a temperature standpoint to use a backfill of crushed tuff, which would be expected to have an effective thermal conductivity of 0.58 to 0.74 W/m·K. However, single waste package temperatures could be 50°C higher than nominal (using average heat loads) because of variability in the waste stream. This variability in waste package temperatures would have potential consequences for waste package and repository performance as discussed in Section 5.2.3 of this progress report. Variations in backfill geometry were found to impact peak temperatures by no more than 40°C. In general, issues of geometry were less important than those of backfill conductivity and time of backfilling. Backfill added much earlier than 100 years after emplacement would require higher effective thermal conductivities to avoid exceeding the cladding thermal goal, so crushed tuff or other readily available and relatively inexpensive materials would not be acceptable if added early. Emplacement drifts cannot be backfilled at time of waste package emplacement with any material without violating the thermal goal for cladding and possibly compromising other waste package materials.

In support of the Engineered Barrier System Performance Requirements System Study, the thermal effects of adding a drip shield placed over the waste package were investigated. Three shield materials (titanium, aluminum oxide ceramic, and Pyroceram) were considered using varying sizes of air gaps between the shield and waste package. Results indicate that adding a thin drip shield would not result in excessive internal waste package temperatures provided the gap between the drip shield and waste package would be kept small. Gaps of up to 6 mm can be tolerated using a Pyroceram (glass-ceramic) drip shield, and gaps of up to 8 mm can be tolerated if a titanium oxide or aluminum drip shield is used.

The error introduced by using a two-dimensional thermal model compared with a three-dimensional thermal model was estimated. Results indicate that the differences are greatly magnified by adding backfill such that peak waste package surface temperatures could be under predicted by 60 to 100°C with a two-dimensional model for waste package spacings similar to that specified in the advanced conceptual design. Therefore, a three-dimensional thermal model is necessary to adequately estimate temperatures at the waste package and the near field when backfill is being evaluated.

The near field with multiple waste packages was evaluated (CRWMS M&O, 1996y) to investigate the thermal effects of reduced waste package spacings and the impact of individual waste package heat load variability. Four waste package emplacement scenarios (all at a nominal 83 MTU/acre mass loading) were considered:

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1. Variable spacings from the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b) to account for the waste loading of each waste package (i.e., higher loading would lead to wider spacings to prevent excessive temperature)
2. Fixed spacing (12.0 m center to center) between waste packages for spent nuclear fuel
3. Fixed spacing (1.0 m end to end) between all waste packages
4. Fixed spacing (0.1 m end to end) between all waste packages.

In the first two scenarios, high-level waste glass packages were inserted (as extra waste packages) in the gaps between spent nuclear fuel packages. For all four scenarios, there were three times as many spent nuclear fuel waste packages as high-level waste glass packages.

For the first scenario, only when waste packages with 21 design basis pressurized water reactor fuel assemblies were assumed did peak fuel cladding temperatures approach the design goal (limit) of 350°C, and all drift wall temperatures would remain comfortably below the limit of 200°C. For the second scenario, when design basis pressurized water reactor fuel waste packages were assumed, the cladding temperature goal was exceeded by about 25°C. However, temperatures for other waste packages would remain below the goal, and the maximum drift wall temperature would be 190°C (near the hottest waste packages). In previous evaluations, the minimum waste package spacing that could reasonably be achieved with large waste packages for pressurized water reactor fuel was estimated to be 12 m. That conclusion is supported by these evaluations. The cladding temperature could be reduced through waste package redesign to allow spacing of 12 m. However, the maximum drift wall temperature cannot be reduced through waste package redesign, so spacing of less than 12 m would not be achievable. For the third scenario, internal temperatures in waste packages containing 21 design basis pressurized water reactor fuel assemblies would reach more than 50°C above the cladding temperature goal. Maximum drift wall temperatures near the waste packages would range from 203 to 229°C. Both of these temperatures are above the 200°C design goal. The fourth scenario predicts maximum drift wall temperatures more than 50°C above the thermal goal, and estimated peak internal temperatures in the waste package with design basis pressurized water reactor fuel would exceed the goal by 75°C. Even for waste packages with average boiling water reactor fuel, the internal temperatures would exceed 300°C. These results indicate that although peak cladding temperatures would be sensitive to the age of the fuel (10-year-old design basis versus 26-year-old average fuel), the maximum drift wall temperatures would depend more on the density of waste packages in the drift than on the output of any single waste package.

An important caveat for the above discussion is that the arrangement of waste packages was not specified in a way to minimize peak temperatures. For example, two waste packages containing 21 design basis pressurized water reactor spent fuel assemblies were always assumed to be adjacent to each other. Therefore, the results of this work are considered conservative. Nevertheless, the results indicate the potential limitations of the "line load" concept (discussed in Section 5.2.3 of this progress report) which includes close axial spacing of waste package. Another caveat relates to the value of percolation flux. The studies cited were performed with

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values of flux lower than the values now believed to be characteristic of the repository horizon. The effect of this difference on the thermal loading conclusions has not yet been assessed.

Waste Package Scale Thermal Analyses

Specific finite element models of waste packages for uncanistered fuel have been developed to address potential changes (improvements/advances) in the waste package designs. New designs of waste packages are being evaluated that have capacities of 21 pressurized water reactor assemblies and 44 boiling water reactor fuel assemblies. The effects of potential changes in barrier and basket material, basket configuration, and waste package capacity were evaluated with respect to engineered barrier segment requirements. These calculations, which continued throughout the reporting period, will result in specific recommendations for advances in the waste package design effort. One significant result is that there are severe limits on the capacity of waste packages for spent nuclear fuel that do not have baskets. The use of carbon steel tubes (rather than stainless steel-boron tubes as in the advanced conceptual designs) would provide improved thermal conductivity to replace the conductivity that had been provided by aluminum thermal shunts in the advanced conceptual design. Further results of these ongoing considerations will be addressed in the next progress report.

Spent Nuclear Fuel Effective Thermal Conductivity Methodology

In support of current and future waste package thermal design efforts, the Spent Nuclear Fuel Effective Thermal Conductivity Report was completed (CRWMS M&O, 1996z). The objective of the report was to describe the development of effective thermal conductivities for pressurized water reactor and boiling water reactor spent nuclear fuel assemblies as a methodology for predicting (with a high level of confidence) a "best estimate" of peak cladding temperatures for spent nuclear fuel.

The process of developing and validating effective thermal conductivity methodology began with the development of finite element models of various fuel assembly types with fill gas environments of helium, vacuum, nitrogen, and argon. These finite element models were then used as the basis for determining effective thermal conductivities of assemblies with smeared (homogeneous) properties. Effective thermal conductivities were defined using detailed models of intact fuel assemblies evaluated over a range of temperatures and heat loads. Cladding temperatures determined using derived effective thermal conductivities were compared with temperatures computed using other cladding temperature prediction methods, and the finite element models and effective thermal conductivities were benchmarked against spent nuclear fuel cask tests. Excellent agreement was obtained. The finite element spent nuclear fuel assembly thermal models also provided the thermal behavior of fuel assemblies with a dry fill gas, including the effects of channels, water rods, oxidation thickness, and basket wall gradients.

Maximum cladding temperature limits have been established for the storage, transportation, and disposal of spent nuclear fuel. Of the three methods available to estimate fuel cladding temperatures, the effective thermal conductivity method (assuming smeared or homogeneous properties to represent the assembly) as just discussed is the most flexible and cost

effective. Although this method does not provide detail within the fuel assembly, it can accurately predict maximum assembly temperatures, provided the effective thermal conductivity has already been developed for the assembly type and fill gas being considered. The method is applicable to finite element or finite difference analyses and allows extrapolation to different assembly sizes, configurations, and fill gases. A second method, the Wooton-Epstein correlation (Wooton and Epstein, 1963) using maximum fuel basket temperatures, is less desirable because it is an empirical correlation using data from experiments performed in 1963 and applies only to a horizontal pressurized water reactor fuel assembly in air. Although more detailed, the third method of explicitly modeling all the spent nuclear fuel rods (and considering conduction, convection, and thermal radiation) is costly, time consuming and complicated; and it provides detail within each individual spent nuclear fuel assembly rather than in the spent nuclear fuel container being analyzed.

Effective thermal conductivities calculated using discrete model results were found suitable for use in predicting best-estimate temperatures of pressurized water reactor and boiling water reactor fuel assemblies in fill environments of helium, vacuum, nitrogen, and argon (at least for the center of a waste package, where basket thermal gradients are low). This approach should help prevent overprediction of cladding temperatures due to excessive conservatism, which can constraint waste package design and limit the capacity of potential waste package design concepts.

Two effective thermal conductivities have been developed, one that is a function of basket wall temperature and one that is a function of median assembly temperature. Both of these can be applied to containers in a vertical or a horizontal orientation. For fill environments of helium and vacuum, convection in a vertical container is minor or nonexistent, and the effective thermal conductivity method would provide a best-estimate prediction of peak cladding temperatures. For buoyant fill gases such as air, nitrogen, or argon, neglecting convection in a vertical container (a typical industry practice) would result in a small conservative bias when using the effective thermal conductivity method. Also, for horizontal container orientations, contact between the spent nuclear fuel assembly and the basket wall would tend to lower peak temperatures and may result in slightly conservative temperature predictions when the effective thermal conductivity method is used.

In summary, temperature-dependent spent nuclear fuel effective thermal conductivities were found to provide a simple methodology for calculating best-estimate peak cladding temperatures. The methodology has been benchmarked against spent fuel storage test data and complex national laboratory evaluation processes, and it was developed with reproducible calculations using an industry standard code.

Subactivity 1.10.2.3.2 - Structural. The primary effort of the reporting period was the development of the Emplaced Waste Package Structural Capability Through Time Report (CRWMS M&O, 1996aa). The objective of this document was to provide a basis for time-dependent structural analyses. This report focuses on uniform thinning of waste package components and how it relates to certain structural failure mechanisms. It includes a short review that demonstrates how the component thinning results could be used in determining the

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relative and finite structural failure times. The correlation to failure time was based on uniform corrosion models from Total System Performance Assessment - 1995 (CRWMS M&O, 1995a). The degradation levels considered in the report cover repository operations, substantially complete containment, and isolation. When more highly developed corrosion models become available, it will be possible to make more accurate predictions of the condition of the waste package as a function of time. Data from use of models for localized and general corrosion, as well as data on structural impacts of localized corrosion, will be needed for determining the probability of radionuclide release for performance assessment.

The report focused on three types of waste package structural loading: static, rock fall, and seismic. They are discussed further in the following paragraphs. A disposal container for 21 uncanistered pressurized water reactor fuel assemblies was evaluated. This disposal container is described in Section 5.1.1 of this progress report.

Barrier Capability Under Static Loading

Two three-dimensional solid models were used to evaluate waste package barriers receiving structural support from the basket assembly. One was a half symmetry model, that is, half of the package was represented explicitly and the behavior of the other half was derived by using the axial symmetry of the waste package. Using the symmetry reduced both the computer time required and the size of the output files. As the barriers were uniformly thinned to represent degradation, better element resolution was desired, so a quarter symmetry model was developed, allowing greater detail without increasing solution times or output file sizes. The waste package components included in each model were the outer barrier and lids, inner barrier and lids, side guides, corner guides, criticality control plates, and tubes. Loads on the waste package included the individual component weights, the spent fuel assembly load, and, when present, the backfill load. The backfill load assumed was equivalent to that of crushed tuff piled to 0.82 m above the top of the waste package. The emplacement supports were represented by radial displacement constraints.

There are no codes or standards that apply directly to the design of disposal containers. However, the Level A service limits from the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers (ASME, 1995) have been chosen as a guide for setting stress limits for waste package components. In particular, exceeding either the allowable membrane or membrane plus bending stresses given in the code was used as a conservative criterion for containment failure. For static calculations, failure was taken to occur when the stress exceeded the limit in one element. These criteria are considered to be conservative with regard to uniform thinning. However, the degree of conservatism is not known because the impact of localized corrosion has not yet been assessed.

The static analyses of the waste package barriers included a sensitivity study of three effects on barrier performance: (1) the effect of taking structural credit for the basket assembly when analyzing the barriers, (2) the effect of the presence of emplacement drift backfill on the barrier stresses, and (3) the effect of the difference in mass between the original material and the degradation products.

The effect of taking structural credit for the basket assembly when analyzing the barriers was significant, especially when there was substantial thinning of the barriers. When the basket assembly is assumed to support the barriers, the barriers would be able to retain containment until both the inner and outer barriers had degraded almost entirely (2 mm inner barrier thickness remaining from original thickness of 20 mm), and the basket components had begun to thin. When no support from the basket assembly is assumed, the barriers would be capable of retaining containment until the outer barrier had degraded completely and the inner barrier had thinned to 9.5 mm from its original thickness of 20 mm. This amount of degradation is currently estimated to require more than 100,000 years, accounting only for uniform thinning. This level of conservatism (taking no credit for basket support of the barriers) would be appropriate if manufacturing tolerances result in significant clearances between the containment barriers and the basket assembly. If such clearances are present, significant deflection of the containment barriers would occur before the basket assembly would provide internal support.

The presence of backfill and the mass difference between original materials and degradation products had only minor effects on the results, causing the barrier thickness at failure to vary by only a few millimeters (6.5 to 9.5 mm).

Basket Stability Under Static Loading

For calculations of basket stability, the basket was assumed to be loaded by its own weight and the weight of the waste form. The calculations therefore represent basket degradation in a container that is perforated but nevertheless maintains its mechanical integrity. The basket assembly would be made up of four different components: tubes, interlocking criticality control plates, side guides, and corner guides. (See Figure 5-1.) In performing these analyses, it was determined that the side guides and criticality control plates are the basket components critical to maintaining the spent fuel configuration under static loading. The criticality control plates were found to be capable of maintaining the spent fuel configuration without the support of the tubes. The tubes, however, would provide better thermal performance and additional support for the basket assembly. The corner guides would be required to maintain the spent fuel configuration.

The side guides are part of the design for thermal performance and for maintaining the basket configuration. They would be located between the tubes and the inner barrier. On the basis of the loadings analyzed, the capability of the degraded basket to withstand static loading would be limited by the side guide. The side guide could withstand static loading until it had thinned to 3.8 mm, and the calculated time at which it would fail ranges from 44 to 560 years following breach of the barriers. When this level of uniform degradation is reached, the side guide would no longer be capable of supporting the load, and the entire basket structure would shift downward until the criticality control plates and fuel would be resting on the inner barrier. The tubes, made of the same material as the side guide but much thinner, would have completely degraded when this occurred. Following failure of the side guides, corner guide failure might occur, having a similar but less severe impact.

After the guides and tubes had degraded, the criticality control plates would be the only remaining basket structure, and the horizontal plates under the peripheral spent nuclear fuel

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assemblies would be the limiting structures. These plates would be capable of sustaining the bending load until they had thinned to 4.5 mm. This would take between 2000 and 8500 years following breach of the barriers. When failure of these plates occurred, fuel assemblies on the upper side of the basket would load the fuel assemblies on the lower side, probably accelerating complete collapse of the basket structure.

Barrier Capability Under Rock Impact Loading

A full three-dimensional finite-element model of the waste package (including inner and outer barriers) has been developed in accordance with the conceptual designs. A transient dynamic analysis solution was obtained through use of this model, with gravitational acceleration as the load on the system. The rock was taken to be a rigid sphere falling from the roof of a 5.0 m emplacement drift, and the waste package was assumed to be on rigid supports that held it just barely above the invert. Displacement constraints at support locations prevented vertical and horizontal motions of the waste package. There was one support location at each of the extreme ends of the outer barrier. These boundary conditions provide an approach for the simulation of a rockfall event that is believed to be conservative. The assumption of rigid rock and low supports maximizes the amount of energy transferred to the waste package. The spherical rock shape was chosen to make the assumption of rigidity more plausible. A pointed rock, for example, would concentrate the energy on a smaller area of the waste package, but energy could be dissipated in the crushing of the pointed rock.

Dynamic analyses simulating rocks falling onto the waste package have been performed to determine how the critical rock size would vary as the waste package barriers would degrade. The critical rock size is defined as the size and mass of rock that would cause stresses in the barriers equal to defined Level D service limits for the component materials as given in the Boiler and Pressure Vessel Code. The Level D service limits are that the general primary membrane stress intensity may not exceed $0.7 S_u$ and the maximum primary stress intensity may not exceed $0.9 S_u$, where S_u is the minimum tensile strength at room temperature as given in the specification for the material. In this calculation, "failure" of the waste package was taken to occur when the stresses reached the Level D service limits in one element. This criterion is conservative with regard to uniform thinning, though the degree of conservatism is not known because the impact of localized corrosion has not yet been assessed. Thicknesses evaluated ranged from original thickness of the barriers to complete degradation of the outer barrier and an inner barrier thickness of 10 mm, half of the original thickness of 20 mm. The allowable rock size and mass values are summarized in Table 5-1.

As the table demonstrates, the capability of the barriers to withstand rock impact loading would be substantially reduced as the barriers thinned. These results will need to be compared with analyses of rock masses that would be likely to fall on the waste packages to estimate waste package failure caused by rock fall as a function of time. Section 4.1.19 of this progress report discusses preliminary systems analyses of the effect of rock fall on waste package and repository performance.

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Table 5-1. Five Cases Conservatively Predicting Rock Sizes Needed for Failure of One Element

Variable	Case				
	1	2	3	4	5
Outer barrier degradation (%)	0	50	75	100	100
Inner barrier degradation (%)	0	0	0	0	50
Allowable rock mass that does not breach containment barriers (kg)	8000	2500	1000	350	50
Rock size diameter for allowable rock mass values (m)	1.90	1.29	0.95	0.67	0.35
Time to reach degradation level assuming uniform thinning (years)	0	23,000	54,000	>100,000	>>100,000
Drop height (m)	2.23	2.33	2.38	2.43	2.45

The calculation described above is extremely conservative in its treatment of stress; if the stresses equal or exceed the Level D service limits in even one element, the container is said to have failed. A more realistic, but still conservative, approach is to consider that excessive stress will only cause failure of the elements on which the stress acts. Under this approach, containment failure does not occur unless there is a connected row of failed elements that extends from the outer surface of the outer barrier to the inner surface of the inner barrier. A second design analysis was performed (CRWMS M&O, 1996bb) to determine the resistance of current waste package designs according to this more realistic treatment. The rockfall analyses for this study have been performed on waste packages with degradation levels ranging from no degradation to levels at which three fourths of the outer barrier is degraded. The outputs of the analyses performed are related to the percentage degradation in the waste package materials. Degradation of the outer barrier is modeled as uniform general material thinning, which results in weakening of the waste package component.

The results of this rockfall analysis do not relate degradation to time. However, these results will provide a base for time-dependent structural analyses and serve as inputs in determining the expected time of failure of the waste package barriers. The determination of the expected time of failure of the barriers helps provide a basis for determining the probability of spent nuclear fuel release for performance assessment.

Failure in the outer barrier may occur by unstable growth of a pre-existing or a rock-induced crack. However, because of high fracture toughness of ASTM B 443, the inner barrier containment may still provide containment, and radionuclides are not released as long as the inner barrier is intact. For this reason, a fracture mechanics evaluation was not performed on the barriers; such an evaluation is planned for the waste package design in support of the eventual

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license application. Thus, the rockfall analysis reported here determined the critical rock sizes that would breach both inner and outer barriers of the waste package in accordance with the previously stated criteria obtained from the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers. The criterion for resisting failure was that the general primary membrane stress intensity not exceed $0.7 S_u$ and the maximum primary stress intensity not exceed $0.9 S_u$, where S_u is the minimum tensile strength as given in the material specification.

The rock mass and sizes given in Table 5-2 were determined as the bounding results of this analysis because any further increase in the rock mass would breach the containment barriers. The analysis showed that when there is no degradation of the barriers, the waste package would be capable of withstanding the fall of a 38 000 kg rock. When half of the outer barrier is removed the capability of the waste package to withstand a rock fall would be reduced to a 24 000 kg rock. With three fourths of the outer barrier removed the critical rock size would drop to 3500 kg.

Table 5-2. Three Cases Predicting Rock Sizes Required for Loss of Containment

Variable	Case		
	1	2	3
Outer barrier degradation (%)	0	50	75
Inner barrier degradation (%)	0	0	0
Allowable rock mass that does not breach containment barriers (kg)	38 000	24 000	3500
Rock size diameter for allowable rock mass values (m)	3.16	2.71	1.43
Drop height (m)	2.64	2.74	2.79

Waste Package Capability During Seismic Events

Finite-element analysis code was used for seismic analysis of a waste package under various degrees of material degradation. The models developed for this analysis were one-quarter and one-half symmetry three-dimensional finite-element models. The analysis incorporated the waste package outer barrier and lids, inner barrier and lids, basket tubes, criticality control plates, side guides, and corner guides.

The input is defined as a constant acceleration in a critical frequency range. The acceleration used, $0.66 g$ is as established in (CRWMS M&O, 1994a). Results indicated that with complete degradation of the outer barrier, with uniform inner barrier thinning of 18 mm, and with carbon steel basket component uniform thinning of 5 mm, the waste package would still be capable of containing waste and maintaining fuel assembly configuration in the basket assembly.

For this condition, the side guide would be an important component. Thinning of the side guide by 5 mm would be expected between 30 and 340 years after breach of the containment barriers. Seismic loading would cause component failure when half of the original thickness (3.5 mm) has been removed from the criticality control plates. Therefore, the critical level of degradation for seismic loading is bounded by degradation of the side guide and criticality control plates.

Spent Nuclear Fuel Structural Capabilities

Evaluations were performed to determine if degradation products would structurally load the spent nuclear fuel assemblies. These calculations were necessary because the degradation products occupy a greater volume than the original materials. The results of the volume calculations showed that the volume of the degradation products would be insufficient to fill the gap between the tubes and the fuel assemblies. Therefore, the fuel rods would not experience significant compression loads from degradation products.

Evaluations were also performed to determine if the fuel rods in the spent nuclear fuel assemblies could withstand static loads after the complete collapse of the basket assembly and barriers. Fuel rods from the fuel assemblies on the bottom side of the waste package were analyzed because they would be under the highest loading. The results of the analysis indicated that the maximum bending stress would be 57.2 MPa. With an allowable stress intensity of 348.2 MPa for the fuel rod cladding material (including effects of radiation), the margin of safety is 5.1. For the conditions assumed here, the fuel assemblies could withstand the static load following complete collapse of the waste package barriers and basket assembly without fuel rods rupturing.

Subactivity 1.10.2.3.3 - Criticality. The purpose of this subactivity is to perform disposal criticality control analyses and to determine the impact of criticality control issues on waste package design. The criticality activities performed included work in the following areas: determining the conditions under which criticality is possible and the probability of criticality should those conditions occur, calculating the consequences of criticality if it is assumed to occur, writing and issuing the Disposal Criticality Analysis Methodology Technical Report (CRWMS M&O, 1996c), developing the approach for integral principal isotope burnup credit, supporting the differential actinide-only burnup credit effort, performing evaluations of updated designs, and other supporting efforts concerning neutronics issues for disposal. The work performed in each of these areas is discussed below.

Occurrence of Criticality: Possibility and Probability

The possible occurrence of criticality external to the waste package that might follow the degradation of waste packages containing commercial spent nuclear fuel was evaluated. The general methodology for identifying and generating potentially critical configurations was refined to ensure that all representative configuration types are considered. The Monte Carlo code MCNP was then used to calculate k_{eff} for the representative configurations. The results were reported in Probabilistic External Criticality Evaluation (CRWMS M&O, 1996cc) and are summarized in the following paragraphs.

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The possibility of occurrence of criticality in fissile material resulting from commercial spent fuel is reduced by the presence of uranium-238, which is a moderately strong neutron absorber. Conversely, the potential for criticality could be enhanced by plutonium being left behind after the more soluble uranium-238 has been removed from the degraded waste package. To examine this possibility, the coupled rate equations modeling waste form dissolution, release of plutonium and uranium from waste package, and radioactive decay of plutonium-239 to uranium-235 were solved numerically (using a specially written computer code).

The resulting effect on criticality potential would depend on the uranium solubility, which could range from 1 ppm to 2400 ppm for the range of possible water chemistries. For uranium solubilities less than 200 ppm, there would be very little increase in effective enrichment because the uranium release rate would be so slow that most of the plutonium-239 would decay to uranium before much of the uranium initially present would be released from the waste package. (Effective enrichment is defined as total uranium equivalent fissile content divided by total uranium plus plutonium, where the uranium equivalent of plutonium was taken as 1:1 and 1.25:1 to reflect the range of greater criticality effectiveness of plutonium, depending on geometry and the range and variety of neutron absorbers.) For uranium solubilities greater than 200 ppm, effective enrichment could significantly increase. As long as the uranium solubility is less than 2400 ppm, however, there would be very little fissile material left in the waste package by the time the effective enrichment would have significantly increased. For example, by the time the effective enrichment would have doubled (to four percent), only 10 percent of the original fissile inventory would be left in the waste package. Alternatively, by the time the total fissile content in the waste package would have decreased by 50 percent, the effective enrichment, for typical spent nuclear fuel, would be no more than 2.2 percent. MCNP calculations have shown that the reduced total fissile inventories more than negate the small increases in effective enrichment, which implies plutonium being left behind in the waste package which would not significantly enhance the criticality potential there.

The effective enrichment inside the waste package serves as an upper bound for the effective enrichment outside the waste package. The effective enrichment outside the waste package could only decrease as fissile material leaves the waste package because the lower solubility of plutonium means the plutonium would always be preferentially left behind, so external concentrations of fissile material would always be depleted of plutonium by comparison with internal concentrations. Therefore there could be no enhancement of external criticality by the mechanism of effective enrichment enhancement.

It has been suggested that the possibility of external criticality could be enhanced by uranium or plutonium concentration by the zeolite clinoptilolite (by the ion exchange process of replacing calcium ions with uranium or plutonium ions). The maximum possible concentration of fissile material in the zeolite has been calculated under the very conservative assumptions that a fissile ion replaces each calcium ion and that clinoptilolite occupies 70 percent of the rock. Given the further conservative assumptions that the rock has 30 percent pore space filled with water and that the effective enrichment of the uranium and plutonium is the initial emplacement value (1.94 percent). The analysis showed that criticality could not occur in the zeolite layer no matter how large the spatial extent of the zeolite deposit. As fissile material is removed by

zeolite, there would be a corresponding reduction in the amount of uranium reaching any organic reducing zones, a phenomenon that provides an additional measure of conservatism for the evaluation of those reducing zones that is summarized in the following paragraphs.

An external criticality in the reducing zones would require (a) a reducing zone that can concentrate sufficient fissile material from ground water, (b) a ground-water flow from the repository containing sufficient material to be concentrated, and (c) an encounter of the fissile-bearing ground-water flow with the reducing zone.

A review of the literature on mineralization and reducing zones showed that the strongest reducing zones for the concentration of uranium (irrespective of geologic formation) are associated with concentrations of organic material. The closest location beneath Yucca Mountain where organic material could occur is at the base of the tuff (1100 to 1200 m below the surface), where it might remain from just before the volcanic period that laid down the tuff. Organic material could not remain within the tuff itself during the volcanic period because it would be burned by the high temperatures. The model for the organic concentrations that might possibly exist at the base of the tuff was the organic tree trunks (logs) found to concentrate uranium in the Colorado Plateau region. This analog was chosen to be as conservative as possible (overestimating the probability of significant occurrence of organic material). This model is conservative because log organic deposits in the Colorado Plateau gave rise to the richest known uranium deposits in the United States, and because the rock below the tuff at Yucca Mountain is much less favorable to the concentration of organic material than is the sandstone in which the logs are found in the Colorado Plateau. Furthermore, there is no scientific evidence of any such occurrences beneath Yucca Mountain.

With the further conservative assumption that a fissile-bearing flow from the repository contacts the reducing zone created by the postulated log occurrence, an initial estimate of the possibility of criticality occurrence can be made. The maximum grade ore ever found in the Colorado Plateau region (20 percent uranium by weight) was conservatively assumed to be concentrated in the largest known log (1.22 m in diameter), while the surrounding rock has 40 percent pore space filled with water. An MCNP calculation has shown that this concentration would be subcritical.

The only possibility for accumulation of a critical mass of fissile material would require several logs in close proximity. A conservative estimate of the combined probability of a sufficient concentration of organic material and an encounter of that concentration by a sufficiently concentrated fissile-bearing ground-water flow large enough to precipitate a critical mass of low enriched uranium from commercial spent nuclear fuel is so small as to be extremely unlikely. (The calculation gives a result of less than 2×10^{-15} per year, which is negligibly small.)

Consequences of a Criticality (Assuming That Criticality Does Occur)

Although the probability of a criticality event inside or outside the waste packages is likely to be small, full assessment of the risk posed by criticality requires analysis of the consequences of criticality events should one or more occur. An inevitable consequence of a criticality would

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be an increase in radionuclide inventory. The primary determinants of this increase would be the power and duration of the criticality. Of secondary importance would be the temperature and concentration of the neutronically active species. Detailed results on the consequences of criticality have been published in the Probabilistic Criticality Consequence Evaluation (CRWMS M&O, 1996dd); the results and the bases used to calculate the consequences are summarized here.

The bases used to calculate the consequences of an internal criticality were as follows:

- The waste package temperature was defined by the temperature at which the rate of evaporation from the surface of the water (assumed to just cover the topmost assemblies) would balance the water flow incident on the waste package. This flow rate was conservatively approximated by multiplying the infiltration rate by the waste package area, where the infiltration rate was conservatively assumed to be 10 mm/yr.
- The drift wall temperature was determined by repository-scale and drift-scale hydrothermal calculations summarized in Total System Performance Assessment - 1995. Beyond 10,000 years (which is less than the earliest time at which sufficient neutron absorber material could have been removed from the waste package to permit a criticality) (CRWMS M&O, 1996bb), this temperature would be only slightly above ambient and would be well below the boiling temperature of water under repository conditions.
- The power level of the internal criticality would be that power level necessary to support the rate of heat dissipation to the environment (a) by radiation to the drift wall and conduction through the rock invert, which is driven by the temperature gradient between the waste package and the drift wall; (b) by heating the infiltrating water from the general repository temperature to the waste package temperature; and (c) by evaporating the water (heat of vaporization) from the surface of the water within the waste package.
- The duration of the internal criticality would be limited by the duration of the peak water flow to the waste package needed to maintain the power level. This is currently assumed to be less than 10,000 years (CRWMS M&O, 1996bb).
- The sustainability of this criticality with respect to the balance between fissile species (generally consumed by the criticality) and neutron absorbers (generally produced by the criticality) was verified by using the point depletion code SAS2H to calculate the species amounts at several times during the criticality, and using these amounts as input to MCNP to calculate the k_{eff} at each of the times. The calculated k_{eff} remained within calculation error (.002) of its initial value (.897).

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The bases used to calculate the consequences of external criticality were as follows:

- The average temperature of the critical mass was estimated as the boiling temperature of water at 50 atm (about 265°C). The reason for use of this value is that the most probable place where a reducing zone may occur would be in organic material at the base of the tuff, which is typically 500 m below the water table, giving rise to a hydrostatic pressure of 50 atm.
- The maximum power would be the power from fission required to maintain the average temperature of the critical spherical configuration against heat conduction out from the sphere. A higher power level would cause the water moderator to boil at a rate that would result in net loss of moderator and thus cause the power to be reduced. This power would be determined by the boiling temperature of water and would be less than 5 kW.
- The sustainable power would be determined by the rate at which new fissile material would be transported to the critical mass to replace the fissile material being consumed. For the highest water flow and largest solubility of uranium considered, sustainable power would be less than 1.5 kW.
- The duration of an external criticality, at a specified sustained power level, would be determined by the duration of flow of fissile material-bearing groundwater from the repository. The duration of fissile material-bearing flow could be no greater than the duration of flow of water incident on the waste package used to measure the duration of internal criticality because without flow on the waste package the fissile material-bearing water would cease. The increase in radionuclide inventory has been calculated for a flow rate cycle, going from the peak power sustained for 10,000 years to a minimum of 0 watts over a period of 100,000 years; this period is based on the postulated Milankovitch glacier cycle and is consistent with that used in Total System Performance Assessment - 1995. This postulated glacier cycle is believed to represent the length and nature of a flow rate cycle in Yucca Mountain. The duration of peak sustainable power is conservatively estimated to be less than 10,000 years. Lower levels of sustained power, resulting from lower influx of fissile nuclides, could be sustained for longer periods.
- The increase in radionuclide inventory would be determined by the same methods as were used for the internal criticality, using the computer codes MCNP, SAS2H, and ORIGEN-S.

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The results of the criticality consequence evaluations can be summarized as follows, for both internal and external criticality:

- The change in k_{eff} over the duration of the criticality would be small, for nominal 10,000 year duration and even for 100,000 year cycling due to temperature and UO₂ infiltration limited power. This result is consistent with the small change in k_{eff} expected for internal criticality that was previously discussed.
- The increase in radionuclide inventory would be only a small percent for a single package and a very small percent for the repository because of the small number of packages that would be expected to go critical.

A potential consequence of a criticality is autocatalytic behavior (positive feedback) from overmoderation. However, the high water concentration required is very unlikely (CRWMS M&O, 1996dd, [Probabilistic Criticality Consequence Evaluation]). Furthermore, that analysis indicated that even if such an autocatalytic criticality did occur, for fissile concentrations typical of commercial spent nuclear fuel, the system would quickly lose enough water (pass out of the autocatalytic, overmoderated range) to move into a negative feedback regime and shut down the criticality.

Disposal Criticality Analysis Methodology Reports

The development of the Disposal Criticality Analysis Methodology Reports (technical and topical) is a major, multiyear task that continued this reporting period. The Disposal Criticality Analysis Methodology Topical Report is intended to present the methodology for performing disposal criticality analysis (including the use of burnup credit) for any fissile waste form, any waste package design, and the proposed repository. The initial version of the report (to be completed in FY 1998) will focus on commercial light water reactor fuel. Additional fuel types that might be emplaced will be covered in amendments to the report. An early milestone in developing the disposal criticality analysis methodology was the completion of the Disposal Criticality Analysis Methodology Technical Report, which was written and issued during this reporting period (CRWMS M&O, 1996c). This report describes the current state of development of the disposal criticality analysis methodology.

Burnup Credit

Seeking burnup credit means seeking regulatory approval to account for the reduced reactivity of spent nuclear fuel as compared with the same fuel before irradiation. Burnup credit is a major aspect of disposal criticality control, and work to obtain it remained a major activity in this reporting period. There are currently two approaches being pursued to validate burnup credit, integral and differential. The integral approach to validation compares the calculated reactivity of spent fuel with a benchmark. The differential approach makes this comparison isotope by isotope. The integral approach is the main focus of disposal activities, while the differential approach is the main focus of transportation activities. Different approaches were

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taken because of the different time periods during which the relevant criticality analyses have occurred.

The integral approach was devised when, with the program redirection and budget reductions, the burnup credit testing budget became insufficient to support the planned viability assessment and the scheduled repository license application submittal date. To meet the schedule within the reduced budget, a new approach was devised to get the required testing data. The original, or differential, approach called for acquiring a statistically valid sample of radiochemical assay data from the range of spent/burnt fuel assembly types planned for disposal and performing spent/burnt fuel critical benchmark experiments to validate the methodology. The integral approach uses commercial reactor critical data, code-to-code validations with the U.S. Nuclear Regulatory Commission (NRC)-licensed reactor physics codes, and existing radiochemical assay data to validate the methodology. The commercial reactor criticals are to be used as spent fuel criticals and for verifying negative reactivity worth of spent nuclear fuel. The validation of the disposal criticality analysis codes with the reactor physics codes (code-to-code validation) is to be used in conjunction with the commercial reactor criticals to provide justification for the isotopics model used as part of the disposal criticality analysis methodology and the burnup credit approach. The commercial reactor critical evaluations were continued during this reporting period. The initial results of the first few detailed evaluations of four commercial reactor critical state points for Crystal River Unit 3 were included in the Disposal Criticality Analysis Methodology Technical Report.

The differential burnup credit approach is being used in an ongoing activity supporting transportation applications. A topical report using actinide-only differential burnup credit is currently under review by the NRC (DOE, 1996n). Actinide-only burnup credit is a subset of the planned principal isotope burnup credit. Actinide-only burnup credit is considered insufficient for disposal plans given current waste package design concepts. The supporting data being developed for each approach (differential and integral) are, when appropriate, also being used for the other approach.

Additional Criticality Evaluations

Preliminary criticality evaluations of the current disposal container designs for uncanistered and high-level waste glass canisters have been delayed because of staffing and budget limitations. These analyses will be performed in FY 1997.

An initial evaluation comparing the MCNP version 4A code against approximately 300 critical benchmark experiments was concluded. The results of the evaluation are a key component of the bias determination in the analysis methodology of the disposal criticality technical and topical reports. The results are included in the recent release of the Disposal Criticality Analysis Methodology Technical Report. The evaluation will be updated in the next reporting period, and the results will be included in the next revision to the Disposal Criticality Analysis Methodology Technical Report.

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Subactivity 1.10.2.3.4 - Cost estimation. The purpose of this subactivity is to provide up-to-date cost estimates for the development and production of waste packages. This activity was part of the waste package fabrication development activity. Cost estimates and manufacturing methods were developed. This is an ongoing activity, and the cost estimates will be continually refined. The disposal container design and materials selection have been substantially changed, and work is in progress to determine how these changes will affect the costs of disposal containers.

Forecast: The following thermal and structural design evaluations are forecast for the next reporting period:

- Thermal analyses in FY 1997 will continue to use three-dimensional models to analyze several waste packages. However, revised design basis fuels will be used to provide extra rigor to support the viability assessment. The three-dimensional models will be used to predict the temperatures of components of the engineered barrier segment outside the waste package. Additional thermal analyses of the interior of the waste package will be used to choose designs that will appropriately control internal temperatures.
- Structural analysis will be extended in FY 1997 to consider components of the engineered barrier segment outside the waste package. Topics to be considered include seismic shaking of the waste package on its supports and damage of waste package supports as a result of rock fall. Design basis events during handling will also be analyzed.

Criticality analyses are planned to:

- Determine the geochemistry of the invert and analyze the potential for precipitation of a critical mass.
- Perform a broader screening of geochemical processes and geologic scenarios to identify any that could produce a sufficiently concentrated reducing zone in tuff (either organic or otherwise) to precipitate a critical mass of uranium from commercial spent nuclear fuel.
- Evaluate the potential for external criticality caused by degradation and transport of highly enriched DOE-owned spent fuel.

A meeting with the NRC is planned for the first half of FY 1997 to discuss the Disposal Criticality Analysis Methodology Technical Report and the methodology it describes. A revision to the Disposal Criticality Analysis Methodology Technical Report is scheduled to be developed in late FY 1997. This revision will describe the further refined and developed methodology. The Project plans to complete the Disposal Criticality Analysis Methodology Topical Report in FY 1998 and submit it to the NRC.

Cost estimation will continue as needed to reflect advances in and revisions to design. This work will eventually support the total system life cycle cost analysis for the 1998 viability assessment.

5.1.4 Design Activity 1.10.2.4 - Material Selection Design Support

The purpose of this activity is to perform analyses and make recommendations based on these analyses for material selection in support of waste package design. Waste package material selection will significantly impact the ability of the waste package components to withstand degradation in the repository environment for an extended period of time.

Subactivity 1.10.2.4.1 - Materials selection process. The purpose of this subactivity is to perform analyses to support materials selection for the waste package.

Because of changes to the waste package designs and recent results on the degradation of materials (see Section 5.1.3 of this progress report), a new analysis of waste package materials for viability assessment has been completed (CRWMS M&O, 1996h). Results for different waste package components are discussed in the following subactivities. The types of disposal containers considered were those listed in Section 5.1.1 of this progress report, except that the disposal container for high-level waste glass was the one developed during advanced conceptual design because DOE-owned spent fuel was not in the Civilian Radioactive Waste Management System (CRWMS) baseline when the work was begun.

For several reasons, it is not yet possible to be certain that the currently selected materials will provide acceptable performance. First, the geometry of the disposal containers and underground facilities is subject to change. Second, even if the final design were known, the environment to which the materials would be exposed is still not well defined. Some waste packages will be hotter than others. It is not yet known how many (if any) waste packages will be exposed to dripping ground water. Third, even if the environment were known, the materials performance would be uncertain. Any laboratory tests will by necessity be of short duration in comparison to the expected life of a repository. These limitations apply to any predictive method. Thus, materials that provide acceptable performance under a variety of conditions have been sought, but because of the uncertainties, conclusions regarding their performance are still preliminary.

The following method was used for materials selection. The disposal containers were divided into components for analysis, and the functions that each waste package component performs were identified. For each function, selection criteria were chosen that would enhance a material's ability to perform that function. The candidate materials were rated against grading scales for these selection criteria, and suitable weighting factors were applied, according to the importance of the criteria in ensuring that the component would perform its functions. The ratings against each selection criterion were totaled, and the materials with the largest total score was selected. Thus, the material chosen should be the most conducive to successful design. The following subsections describe the selections made for various components.

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The components, selection criteria, and weighting factors are listed in Table 5-3. For example, as shown in the table, a heavy weighting factor (40) was applied to the chemical performance of the corrosion-resistant barrier for spent nuclear fuel, but a light weighting factor (5) was applied to cost. As a result, corrosion resistance was very important in determining which material was selected, but cost was much less important. No weighting at all was applied to thermal performance for the containment barriers because variations in their thermal performance would have little impact on the ability of the repository and spent fuel to meet their thermal goals. Many of the selection criteria were further sub-divided. For example, mechanical performance was rated by examining yield strength and tensile elongation, and fabricability included formability, weldability, and inspectability. Detailed justifications for the weighting factors and descriptions of how the selection criteria were used to rate the materials were given in the analysis (CRWMS M&O, 1996h).

Table 5-3. Selection Criteria and Weighting Factors for Components of Disposal Containers

Selection criterion	Weighting factors of disposal container components for						
	All disposal containers		Uncanistered spent nuclear fuel only				High-level waste glass only
	Corrosion allowance barrier	Corrosion resistant barrier	Fuel basket tubes	Fuel basket plates	Fill gas	Basket guides	Canister guide
Mechanical performance	10	5	10	10		25	40
Chemical performance	15	40		20			
Predictability of performance	20	20		10			
Compatibility with other materials	15	10	20	10	60	20	20
Fabricability	30	15	20			20	20
Cost	10	5	25	10	15	20	20
Previous experience	10	5		5			
Thermal performance			25	15	25	15	
Neutronic performance				20			

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Lists of candidate materials were developed from previous recommendations. To avoid favoring individual suppliers, ASTM designations for materials were used whenever possible. Because the ASTM provides few specifications for gases, generic chemical names were used. ASTM coverage of neutron-absorbing materials is also limited, so both proprietary grades and ASTM grades were considered.

Subactivity 1.10.2.4.2 - Container shell. The purpose of this subactivity is to determine the materials of choice for the waste package containment barriers. The barriers include a corrosion allowance barrier and a corrosion resistant barrier.

Lists of candidate materials were developed from previous recommendations (McCright, 1995). For the corrosion allowance barrier, the candidate materials were as follows:

- ASTM A 387 Grade 22 (alloy steel, 2¼ percent Cr - 1 percent Mo)
- ASTM A 516 Grade 55 (carbon steel, 0.26 percent C maximum)
- ASTM A 516 Grade 70 (carbon steel, 0.31 percent C maximum)
- ASTM B 171 C71500 (70-30 cupronickel)
- ASTM B 127 (Monel® 400).

For the corrosion-resistant barrier, the candidate materials were as follows:

- ASTM B 265 Grade 12 (titanium with 0.3 percent Mo, 0.8 percent Ni)
- ASTM B 265 Grade 16 (titanium with 0.06 percent Pd)
- ASTM B 424 N08825 (Alloy 825)
- ASTM B 443 (Alloy 625)
- ASTM B 575 N06022 (Alloy C-22)
- ASTM B 575 N06455 (Alloy C-4)
- ASTM B 582 N06030 (Alloy G-30)
- ASTM B 582 N06985 (Alloy G-3).

Two of these materials were added after the initial list was developed. ASTM A 516 Grade 70 was added because of its mechanical strength, and ASTM B 443 was added because of favorable Project experience (CRWMS M&O, 1996h) with weld deposition of this composition.

Because of differences between spent nuclear fuel and high-level waste glass, separate evaluations were made of the compatibility of the container materials with the two types of waste forms. In spite of these differences, ASTM A 516 Grade 55 or 70 was selected as the corrosion allowance barrier material, and ASTM B 443 was selected as the corrosion resistant barrier material for both waste forms. This selection is consistent with the Project's draft waste containment and isolation strategy (DOE, 1996o), which notes that dissolution rate of waste glass will have little effect on peak doses. This finding allowed previous concerns about materials interactions between carbon steel and the high-level glass to be resolved. Current information is insufficient to determine whether ASTM A 516 Grade 55 or ASTM A 516 Grade 70 will provide better performance; a choice between them will require additional engineering analysis.

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The nickel-base alloys ASTM B 443, ASTM B 575 N06022, and ASTM B 575 N06455 are all fairly similar, and their scores were closely clustered. Future information may show that one of the other materials is better suited for the application than ASTM B 443.

Subactivity 1.10.2.4.3 - Shield plug. The purpose of this subactivity is to determine the materials for the waste package shield plug.

A shield plug is not included in the current design of the disposal container. Accordingly, no effort has been made in selecting shield plug materials. No work is forecast in this area.

Subactivity 1.10.2.4.4 - Spent nuclear fuel basket (structural/thermal). The purpose of this subactivity is to determine the structural materials for the basket to be contained inside the waste package. All containers for spent nuclear fuel incorporate basket assemblies. These assemblies provide structural support for the spent nuclear fuel assemblies, assist in heat transfer, and assist in criticality control. This section discusses those components for which criticality control is a secondary function.

The structural and thermal components include the basket tubes and the basket guides. As is discussed in Section 5.1.1 of this progress report, disposal containers for boiling water reactor fuel do not include basket tubes. For both of these components, the list of candidate materials was identical to that for the corrosion allowance barrier. ASTM A 516 Grade 55 or 70 was selected as the material for these components. A choice between the two grades will require additional engineering analysis.

Past efforts in this subactivity were directed toward surveying the corrosion behavior of a range of possible candidate basket materials in short-term scoping tests, using a relatively concentrated solution of species expected to be produced by radiolysis in a waste package after eventual containment failure at long times. These tests plus considerations of neutron absorption effectiveness, mechanical and thermal properties, fabricability, and cost have resulted in boron-containing stainless steels and boron carbide being identified as the leading candidate materials.

During this reporting period, efforts were directed toward developing an understanding of the long-term corrosion behavior of boron-containing stainless steels. A literature search was conducted to elicit what is known about the structure and relevant properties of these materials. The results of this search were then used in conjunction with metallographic examination of a specimen from the scoping corrosion tests to better understand corrosion behavior of these materials. The metallographic examination indicated that the boron-containing phase (mixed metal boride) exhibited higher corrosion resistance than the austenitic stainless steel matrix phase. To focus on the behavior of the boride phase, preliminary macroscopic samples were fabricated having the approximate composition of the dispersed mixed chromium-iron-nickel borides found in the commercial boron-containing stainless steels. Preliminary electrochemical polarization measurements were then made to determine their corrosion rates. The samples were analyzed by scanning electron microscopy, electron microprobe, and secondary ion mass spectroscopy to determine their homogeneity and stoichiometry. The general trends in the electrochemical data were as expected, but the analyses of the samples indicated that the boron-metal stoichiometry had

varied from that desired and that excessive impurities were present. This work has provided the information necessary to refine the fabrication process so that samples produced more accurately reflect the borides found in the commercial stainless steels, and to make detailed changes in the activity plan.

A literature search was also conducted on the oxidation behavior of boron carbide in various tested environments. Although boron carbide appears to perform well in moderate-temperature air and water environments, how it will behave in the chemical and radiation conditions in the repository must be determined. Further work on this material will depend on available funding and resources, but the next step will be to perform a scoping, gamma-irradiated corrosion experiment on boron carbide samples to measure the resulting dissolution of boron. This experiment is planned to be performed next reporting period

Forecast: Basket materials structural work will continue on the mixed metal borides found in the boron-containing stainless steels. The activity plan will be changed to reflect what has been learned. Macroscopic samples of mixed metal borides that more accurately reflect those of interest will be fabricated, characterized, and tested by electrochemical polarization to determine their corrosion rates. The goal will continue to be to establish a basis for projecting long-term behavior of these materials in the potential repository.

Subactivity 1.10.2.4.5 - Spent nuclear fuel basket (criticality). The purpose of this subactivity is to determine the materials to be added to the basket to control criticality in the waste form. This section discusses those components for which criticality control is the primary function, although these components may also perform structural and thermal functions.

The basket criticality control material was chosen for the design to support the 1998 viability assessment. In current designs, the criticality control components take the form of slotted, interlocking plates. Candidate materials for the basket plates were as follows:

- ASTM A 887 Type 304B3 Grade A
- ASTM A 887 Type 304B4 Grade A
- ASTM A 887 Type 304B5 Grade A
- ASTM A 887 Type 304B6 Grade A
- Neutronit A976 or equivalent
- Neutronit A978 or equivalent.

The compositions specified in ASTM A 887 are like that of ASTM A 240 Type 304 (Type 304 stainless steel) but with varying amounts of added boron. Neutronit A976 and A978 are grades of plate produced by Böhler Bleche GmbH of Mürtzzuschlag, Austria. The composition of Neutronit A976, like that of the ASTM A 887 Grade A types, is similar to that of ASTM A 240 Type 304 with added boron. In contrast, the composition of Neutronit A978 is more like that of ASTM A 240 Type 316 (Type 316 stainless steel), again with added boron. The primary difference between Type 304 and Type 316 stainless steels is that the latter contains molybdenum.

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The candidate materials are all fairly similar, and making a choice was difficult. The ASTM A 887 Grade A types provide better mechanical properties, but Neutronit A978 is expected to provide better resistance to pitting corrosion because of its molybdenum content. Because the weighting for chemical performance was greater than that for mechanical performance, Neutronit A978 or equivalent was chosen as the basket plate material for viability assessment.

Subactivity 1.10.2.4.6 - Filler material. The purpose of this subactivity is to consider materials for a filler that might be added to the waste package to displace potential neutron moderators and help control criticality.

With current designs, disposal containers for uncanistered fuel are not expected to require filler material for criticality control. Disposal containers for canistered fuel may require filler material. However, because of the Project emphasis on uncanistered fuel, no additional work on filler material is planned.

Recent work on processes for inserting filler material into waste packages is discussed in Section 5.4.5 of this progress report.

Subactivity 1.10.2.4.7 - Fill gas. The purpose of this subactivity is to determine the appropriate choice of inert material for fill gas to be added to the waste package.

Helium continued to be the fill gas of choice, though this choice was re-examined this reporting period.

The following fill gases were considered as candidate materials:

- Vacuum (classification of vacuum as a gas is arbitrary)
- Helium
- Carbon dioxide
- Nitrogen
- Argon
- Dry air
- Environmental air.

The most important characteristics of a good fill gas are inertness and high thermal conductivity. Helium provides a good combination of these properties and was again selected as the fill gas for the waste package design to support viability assessment.

Forecast: Work on materials selection will continue. A formal reevaluation of waste package materials is not expected during viability assessment design, so materials identified in this section as selected are likely to be current for some time.

5.1.5 Design Activity 1.10.2.5 - Performance Evaluations

This design activity includes work on materials performance. Issues addressed are container oxidation and corrosion, degradation by mechanical stress, and thermal degradation of fuel cladding.

Subactivity 1.10.2.5.1 - Container oxidation and corrosion. The purpose of this subactivity is to analyze degradation of potential waste package container materials as a result of oxidation and corrosion.

Thinning of various waste package components was studied to support the development of the Emplaced Waste Package Structural Capability Through Time Report (CRWMS M&O, 1996aa) (see Section 5.1.3 for further information on this report). The corrosion models and near-field environment were based on Total System Performance Assessment - 1995 (CRWMS M&O, 1995a). Results of the corrosion modeling are described in the following paragraphs.

For purposes of calculating the load-bearing capability of the waste package, the corrosion allowance barrier was assumed to be degraded by general corrosion. For a mass loading of 83 MTU/acre, low infiltration, and no backfill, general corrosion of the corrosion allowance barrier is slow, with total removal of the barrier occurring after 100,000 years. As a result, the containment barriers, under the assumed conditions, are expected to retain considerable load-bearing capability for a long time.

In contrast to the long times for general corrosion of the corrosion allowance barrier, Total System Performance Assessment - 1995 predicted that loss of containment would occur fairly early, with half of the containers failing by 3200 years (with no backfill) or by 4000 years (with backfill) after emplacement. It should be noted that the process models used for waste package degradation in Total System Performance Assessment - 1995 were very preliminary. The short times for loss of containment and long times for removal of the corrosion allowance barrier reflect the effects of localized corrosion in causing early penetration of the containment barriers.

Once the containment barriers have been penetrated, corrosion of the basket can begin. Because the near-field humidity and temperature are time dependent, the rate of degradation of the basket components would also depend on the time at which containment is lost. In addition, the rate of degradation would depend on whether backfill is present. In any case, the time for complete corrosion of the carbon steel basket guides would vary from about 100 years to over 600 years from the time of containment failure. As is discussed in Section 5.1.3 of this progress report, the guides would fail mechanically at shorter times, while some of the guide thickness would still be present as metal. The basket plates, made of borated stainless steel, would be substantially more corrosion resistant. On the basis of data from immersion testing, the plates were estimated to fail 2000 to 8500 years after containment failure. These failure times are for mechanical failure in bending under the loads imposed by the spent fuel. Significantly more time would be necessary to completely corrode the plates.

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Subactivity 1.10.2.5.2 - Degradation of fuel cladding. The purpose of this subactivity is to analyze the degradation of spent nuclear fuel cladding as a result of temperatures and stresses. Fuel cladding may be useful as a barrier against release of radioactive materials to the environment, though credit has not been taken for the cladding in total system performance analyses conducted to date.

Past work on cladding degradation has focused on mechanisms such as creep rupture and oxidation. The environment is assumed to impose a temperature field, and, for some mechanisms, to provide oxygen. For example, creep rupture is assumed to proceed as a result of stresses imposed by pressurization gas and released fission gas. Mechanisms such as these are important to consider for periods in which the containment barriers are intact or even when the containment barriers are breached but the fuel remains dry and the waste package retains its mechanical integrity.

At long times, loss of mechanical integrity would expose the cladding to mechanical loads and the cladding would be subject to mechanical failure. Work on mechanical loading is described in Section 5.1.3 of this progress report under Subactivity 1.10.2.3.2.

Forecast: Work during FY 1997 will include a survey of manufacturers and users of nuclear fuel to determine if additional information is available on cladding degradation. Additional information on cladding degradation will be incorporated into total system performance assessment models.

5.2 INTERACTION BETWEEN THE WASTE PACKAGE AND THE POSTEMPLACEMENT NEAR-FIELD ENVIRONMENT (SCP SECTION 8.3.4.2)

5.2.1 Design Activity 1.10.1.1 - Consideration of 10 CFR 60.135(a) Factors

The purpose of this activity is to explicitly show that the factors specified in 10 CFR 60.135(a) for interactions between the waste package and its environment have been considered in waste package design. These factors include the in situ physical, chemical, and nuclear properties of the waste package and the effect of processes such as solubility, oxidation, corrosion, and hybridizing.

Analysis of Thermal Loading Options

Three-dimensional calculations are required to adequately represent drift-scale thermal-hydrological behavior that will result from the emplacement of waste packages in the potential nuclear waste repository at Yucca Mountain. In previous reporting periods, a three-dimensional, drift-scale, multiple-waste package model, based on the NUFT code, was developed to perform such calculations. Also, calculations were previously performed to compare two fundamentally different ways that waste packages can be arranged in the repository, including the advanced conceptual design and the line-load design. A major objective of this work has been to examine differences between the two designs (for the reference areal mass loading of 83.4 MTU/acre) with

respect to temperature, relative humidity and liquid-phase flux experienced by waste packages. These parameters would strongly affect waste package integrity as well as the eventual dissolution of the waste form and the release of radionuclides from waste packages and the engineered barrier system. Corrosion model calculations have shown that high relative humidity can cause waste packages to be breached within a few thousand years, whereas sufficiently low relative humidity can allow waste packages to remain intact for tens to hundreds of thousands of years. A major factor in selecting a repository design is that waste package heat generation (from radioactive decay heat) varies substantially in the waste package inventory, ranging from virtually "cold" defense high-level waste that generates a relatively small amount of heat to very "hot" high-burnup spent nuclear fuel that initially can generate as much as 18 kW per waste package. The influence of waste package heat output variability on temperature, relative humidity, and liquid flux experienced by waste packages is markedly different for the two waste package arrangements.

The hydrological modeling effort during this reporting period supported the Engineered Barrier System Performance Requirements System Study, the 1996 Thermal Loading Systems Study, and total system performance assessment. The work was also included in the Near-Field and Altered Zone Environment Report, Revision 1 (Wilder, 1996). This work included sensitivity studies that considered a broad range of engineered system and natural system parameter values, including the following:

- Areal mass loading: Values of 25, 45, 83.4, 100, and 120 MTU/acre were considered.
- Lineal mass loading: Values of 0.46, 0.94, and 1.11 MTU/m were considered.
- Axial waste package spacing: Advanced conceptual design axial waste package spacing, with a variable center-to-center waste package spacing ranging from 10.25 to 14.62 m, and end-to-end line-load waste package spacing with 0.1-m gaps between waste packages and 1.0-m gaps between waste packages were considered.
- Drift spacing: Values of 22.5, 41.8, and 75.2 m were considered for the advanced conceptual design axial waste package spacing. Values of 37.4, 44.9, 53.8, 100, and 180 m were considered for the 1.11-MTU/m line-load design.
- No-backfill cases versus backfill cases: For both sets of cases, the drift would be left open for 100 years. For the backfill cases, the backfill is emplaced at 100 years (just before repository closure).
- Backfill configuration: Full backfill, level-partial backfill, and sloping-partial backfill scenarios were considered.
- Waste package configuration: Center-in-drift emplacement and off-center in-drift emplacement were considered.
- Waste package emissivity: Values of 0.3 and 0.8 were considered.

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- Invert/backfill thermal conductivity: Values of 0.3 and 0.6 W/m^{°K} were considered.
- Drift diameter: Values of 3.0, 4.0, 5.5, and 6.5 m were considered.
- Invert hydrological properties: A sand-like invert (i.e., a granular material with nonporous grains) and crushed TSW2 tuff (which has porous grains) were considered.
- Ambient percolation flux: Values of 0.0, 0.05, 0.3, 1.0, and 5.0 mm/yr were considered.

For the engineered system parameters considered, conditions on waste packages and along the drifts were most sensitive to lineal mass loading, axial waste package spacing, and backfill thermal conductivity. The reduction in relative humidity that would arise from rock dryout would be very sensitive to ambient percolation flux over the range 0 to 5.0 mm/yr. For percolation flux less than 0.05 mm/yr, the magnitude and duration of rock dryout for the advanced conceptual design layout would be quite substantial, while for percolation flux greater than 5.0 mm/yr, the magnitude and duration of rock dryout would be largely suppressed for the same repository design. Additional details are provided in Section 5.2.3 of this progress report and in the Near-Field and Altered Zone Environment Report, Revision 1.

The design approach in the MGDS Advanced Conceptual Design Report attempts to uniformly distribute the waste package decay heat over the repository area by placing the waste packages with roughly the same axial and lateral spacing. This approach seeks to limit the peak temperatures on the hottest waste packages. The relatively large axial spacing between waste packages in this approach would cause a potential performance cost. This large spacing would cause the waste packages to be thermally isolated from one another; consequently, there would be a large variability in temperature, relative humidity, and liquid flux at the waste packages and along the walls of the drifts. Large gradients in temperature and the partial pressure of water vapor along the drifts could cause a mechanism called the "cold-trap" effect whereby water vapor would be transported (by gas-phase advection and diffusion) from areas of higher temperature and vapor pressure to areas of lower temperature and vapor pressure where it would condense. This effect could result in a liquid film and relative humidity as high as 100 percent on waste packages. Large condensation rates could arise in the cooler areas that result in liquid-phase flux on waste packages; if waste packages have been breached, this flux might contact the waste form and eventually transport radionuclides out of the waste packages and possibly into the near-field rock.

The line-load design approach would lineally concentrate the waste package decay heat to the greatest possible extent by placing the waste packages nearly end to end along the drifts. For a given areal mass loading, this would allow for the greater spacing between drifts and would require smaller total length of emplacement drifts. An example of this approach assumes a 0.1-m gap between waste packages, resulting in a lineal mass loading of 1.11 MTU/m and a drift spacing of 53.8 m. In spite of the large differences in heat generation among the various waste packages, the highly efficient thermal-radiative waste package-to-waste package heat transfer facilitated by the end-to-end waste package spacing would cause the line of waste packages to function as a more uniform line-heat load. Consequently, the line-load design would generate more uniform temperature, relative humidity, liquid saturation, and liquid-phase flux along the drifts than would

the advanced conceptual design; the more uniform temperature and vapor pressure along the drifts would suppress the cold-trap effect. Moreover, the high axial heat conductance along the line of waste packages would homogenize some of the effects of natural system heterogeneity along the drifts, as well as lessen some of the "edge effects" that would occur at the edge of the repository, such as enhanced cooling and rewetting, and repository-scale condensate shedding. All these edge effects would tend to cause larger liquid-phase fluxes at the edge of the repository (compared with those at the center of the repository). In effect, the line of closely spaced waste packages would serve as a preferential heat-flow conduit that would allow heat to be delivered to areas of the emplacement drifts that would otherwise be more vulnerable to edge effects.

The higher lineal mass loading in the line-load design approach would result in more locally intensive (and uniform) rock dryout around the drifts, and the larger drift spacing would allow for more effective condensate shedding between the drifts, thereby facilitating less condensate buildup above the drifts. For percolation fluxes of 0.3 mm/yr or greater, the lineal mass loading in the advanced conceptual design would not be sufficient to partially dry out, even for a limited period of time, all portions of the rock adjacent to the drift walls; consequently, humid conditions would always prevail along the portions of the drifts containing the cooler waste packages. Moreover, the wet portions of the advanced conceptual design drifts would experience heat-pipe conditions at the upper drift wall, resulting in condensate flux into the drift.

Despite the advantages of the line-load design just described, the 1996 Thermal Loading Systems Study has recommended not making the line-load design the baseline repository loading approach because of concerns about potentially higher peak fuel and drift wall temperatures that could lead to exceeding thermal goals for these parameters. (See Section 4.1.16 of this progress report for additional information on this study.) This recommendation is currently being evaluated.

Thermal-hydrological analysis of backfill in support of the Engineered Barrier System Performance Requirements Study is discussed in Section 4.1.19 of this progress report.

Forecast: Modeling work next reporting period will focus on developing the ability to more accurately account for (a) spatially variable ambient percolation flux distributions, (b) fracture-matrix interaction, and (c) spatially variable natural system properties such as bulk permeability in the drift-scale and hybrid drift-scale–mountain-scale thermal-hydrological models. A major goal of this effort is to develop the ability to more accurately predict seepage flux distributions along emplacement drifts. The thermal-hydrological modeling effort will closely collaborate with site-scale thermal-hydrological modeling activities and with altered zone activities. There will also be increased effort in modeling drift-scale thermal-hydrological behavior to assist in model abstractions required by total system performance assessment and viability assessment activities.

5.2.2 Study 1.10.4.1 - Characterize Chemical and Mineralogical Changes in the Postemplacement Environment

The purpose of this task is to establish, to the degree required in Performance Issues 1.4 and 1.5 (SCP Sections 8.3.5.9 and 8.3.5.10), the information necessary to characterize the chemical and

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mineralogical properties and processes of the waste package environment for anticipated and certain unanticipated conditions. To accomplish this objective, the study will determine the effects of chemical reactions on rock-water systems of the repository horizon over a range of temperatures and chemical conditions that bound the postclosure waste package environment.

This study had seven activities in the SCP (Activities 1.10.4.1.1. through 1.10.4.1.7). Prior to writing the study plan, the study was divided into two studies (near-field geochemistry and introduced materials). When the near-field geochemistry study plan was drafted, the remaining material was organized differently than in the SCP. To avoid confusion between similarly numbered "old" and "new" activities, the "new" activities were renumbered with higher numbers. The cross linkage of the original activities to the current activities is included in Appendix A of this progress report. The status of the current activities is provided below.

The only funded activities in FY 1996 regarding Study 1.10.4.1 were to conclude ongoing work conducted in the areas of reaction kinetics (Activity 1.10.4.1.10) and relative humidity effects (Activity 1.10.4.1.9). Results from these activities were published in Revision 1 to the Near-Field and Altered Zone Environment Report released this reporting period.

Activity 1.10.4.1.8 - Hydrothermal testing of vitric and tuffaceous rocks under saturated conditions. The objective of this activity is to conduct a series of long-term saturated tests to determine the chemical characteristics of the water and the solid phase reaction products that may develop during the interaction of rocks near the potential repository horizon, with reference ground water and other waters at elevated temperatures. Results from these tests are particularly applicable to the deeper, saturated units or to unsaturated units under specific conditions wherein condensate exposes the host rock to above-ambient water availability.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.9 - Hydrothermal testing of vitric and tuffaceous rocks under unsaturated conditions. The objective of this activity is to conduct a series of long-term tests similar to those of Activity 1.10.4.1.8, except that water activity will be controlled to ensure that the activity is always less than 1.0. These tests will evaluate how pore water chemistry and secondary mineralogy may evolve under conditions where water activity is less than 1.0. Reaction rates and mechanisms may also be substantially changed under these conditions. Furthermore, the degree of hydration may change for hydrous phases with a corresponding change in mineral volume. This work is designed to complement other work addressing mineral stability and geochemical evolution of the site (Studies 8.3.1.3.3.2 and 8.3.1.3.3.3, Sections 3.2.5 and 3.2.6 of this progress report).

During this reporting period, experiments in progress were terminated and samples collected and archived for analysis. The results of experimental analysis completed to date were presented in Section 10.4.1 of Revision 1 to the Near-Field and Altered Zone Environment Report. The results indicate that the extent of alteration, as a function of time, would be sensitive to temperature (as expected from well-established models of reaction kinetics) and to the extent of prior alteration. The sensitivity to prior alteration was based on the observation that reaction progress, for any given time or temperature, was less for vitric material in which clay occurred as a ubiquitous but trace

component covering the surfaces of vitric material. As with previous experiments using glassy material from the region, secondary minerals that form are primary zeolites and clays. These results are important because they contribute to defining the response of the rock system to repository conditions and are necessary to determine the waste package chemical environment and repository performance.

Activity 1.10.4.1.10 - Mineral dissolution and precipitation. The objective of this activity is to obtain knowledge of the dissolution kinetics of the phases present in the host rock of the near-field environment and the precipitation kinetics of product mineral phases. This information is required to interpret observed changes in fluid composition and associated development of product mineral phases in hydrothermal rock-water interaction studies.

This activity evaluated apparent discrepancies between laboratory-based and field-based measurements of reaction rates. Precipitation rates for amorphous silica were measured. Rate measurements were carried out in the laboratory using collapsible-bag autoclaves, and were compared with measurements made in the field using a fluidized-bed reactor. The field measurements were made at the Wairakei geothermal field in New Zealand, a key site in which processes relevant for repository evolution can be examined and monitored. The results show that the field-based rates are 10 to 300 times faster than those measured in the laboratory. Observations suggest that these differences are sensitive to temperature and may be influenced by the presence of other chemical species in solution (e.g., aluminum). The precipitation mechanism in the field may be controlled by surface defects. These results are important because they help determine the envelope of uncertainty regarding the time at which changes in the mineralogy and water chemistry would occur during the repository post-emplacement period. This time will in turn be an input to waste package performance evaluations and repository total system performance assessment.

Activity 1.10.4.1.11 - Ion exchange and sorption. The objective of this activity is to obtain knowledge of the effect that ion exchange and sorption may have on the composition of mineral phases and the composition of coexisting water. This information is required to interpret observed changes in fluid composition and associated development of product mineral phases in hydrothermal rock-water interaction studies.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.12 - Rock-water interaction and water chemistry changes in the presence of a radiation field. The objective of this activity is to obtain knowledge of the interaction of ionizing gamma radiation with the air-steam atmosphere and pore water in the near-field environment, with the concomitant spectrum of possible effects on the rock, pore water, and emplaced materials.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.13 - Simulation of rock-water interaction. The objective of this activity is to conduct simulations of the rock-water interaction experiments described in Activities 1.10.4.1.8 and 1.10.4.1.9, using as appropriate, models and data generated from Activities 1.10.4.1.10, 1.10.4.1.11, and 1.10.4.1.12. The activity also simulates natural systems in which processes of

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interest occur. The activity evaluates computer codes and data bases, but does not actually develop codes or data bases. The results of this activity will allow simulations of repository conditions thousands of years into the future.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.14 - Validation of EQ3/6 reaction path modeling codes. The objective of this activity is to validate the EQ3/6 code package to be used in Activity 1.10.4.1.13. This activity will use laboratory hydrothermal experiments not used in previous modeling efforts, analogous natural systems, field-based studies, and ESF studies to validate the calculational approach to reaction path modeling.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.15 - Rock-water interaction simulation of scenarios for license application. The objective of this activity is to use the EQ3/6 code to simulate rock-water interactions for short- and long-term periods, for specific scenarios required for license application. The results will establish the geochemical and mineralogical characteristics of the waste package environment for expected and certain unexpected conditions. The characteristics will include the expected changes in primary and secondary mineralogy that would occur as a result of the interaction of the vadose water with the waste package environment thermal and radiation fields, and with the host rock. The compositional evolution of the vadose water will also be established for the range of temperatures and radiation doses expected in the waste package environment.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.1.16 - Experiments and simulations to determine the effect of geochemical processes on hydrological processes. The objective of this activity is to determine, through experiments, simulations, and study of natural systems, how geochemical processes couple with hydrological processes under the expected post-emplacement hydrothermal conditions. The geochemical processes include dissolution and precipitation of minerals. The hydrological properties of fracture apertures, pore sizes, pore and fracture connectivity, and imbibition properties of the rock will in turn modify the flow pathways and flow rates of water and vapor as heating and cooling of the repository occur. This activity will evaluate the extent to which chemical changes will modify the hydrological properties and will also determine under what conditions these changes are of greatest significance for geochemistry.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: In FY 1997, this task will produce a summary report of the information on the effect of rock-water interaction on water chemistry. This information will be used to determine changes in the local hydrogeological properties of the rock. Dissolution of pre-existing materials could increase local porosity and permeability, while precipitation of minerals could decrease porosity and permeability. Porosity and permeability are important parameters affecting repository performance, so this work will be an input to future repository performance assessments.

5.2.3 Study 1.10.4.2 - Hydrologic Properties of Waste Package Environment

The objectives of this study are to conduct experimental and modeling studies relevant to the range of potential thermal loads to

1. Identify hydrological and transport processes at Yucca Mountain that significantly affect waste package performance, and radionuclide release and transport
2. Develop a detailed conceptual and quantitative understanding of decay-heat-driven flow processes that govern the waste package environment, including temperature, relative humidity, and flow conditions throughout the repository and the engineered barrier system
3. Conduct experiments and develop related models to assess the impact of decay-heat-altered matrix and fracture properties on nonequilibrium fracture flow
4. Develop and conduct laboratory and in situ tests for model validation and hypothesis testing that provide the basis for confidence building for coupled thermal-hydrological-geomechanical-geochemical process models required for total system performance assessment.

This study had three activities in the SCP (Activities 1.10.4.2.1 through 1.10.4.2.3). When the study plan was written and subsequently revised, the material was organized differently than in the SCP. To avoid confusion between similarly numbered "old" and "new" activities, the "new" activities were renumbered with higher numbers. The cross linkage of the original activities to the current activities is included in Appendix A of this progress report. The status of the current activities is provided below.

Work during this reporting period regarding Study 1.10.4.2 was confined to Activities 1.10.4.2.4 (laboratory hydrological property measurements) and 1.10.4.2.6 (model development and analysis of thermal-hydrological flow and transport).

Activity 1.10.4.2.4 - Laboratory hydrological property measurements. The objective of this activity is to determine the hydrological properties of repository horizon Topopah Spring Tuff samples and other rock units that may fall within the thermally altered zone. The properties include effective porosity, saturated liquid- and gas-phase permeability, matrix suction potential vs. liquid saturation, the effective coefficient for the binary diffusion of air and water vapor, and the Klinkenberg coefficient. The properties will be measured under ambient conditions and thermally altered conditions relevant to the heating and cooling cycle for a range of potential thermal loads.

The following paragraphs summarize work performed. This work will help provide an understanding of the saturation process (how water is distributed in rock pore space at different degrees of saturation). Knowledge of this process provides insight on fracture vs. matrix flow regimes and hence helps provide understanding of the fluid flow characteristics of the rock. This

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information will be input into waste package performance evaluations and total system performance assessments.

Electrical properties of Tuff as a Function of Saturation

Rock samples from the ESF were prepared for the measurement of electrical resistivity as a function of water saturation and temperature. These measurements will enable better use of electrical resistance tomographic data to infer water content during the single-heater test and the drift-scale test. The additional data will be used with previously collected data to develop a better understanding of the distribution of water in partially saturated regions as a function of temperature.

Characteristic Curves of Tuff

Experiments to determine moisture retention curves and one-dimensional imbibition continued this reporting period. These experiments measure the water content of USW G-4 cores at high temperatures at various relative humidities, enabling the determination of the characteristic curve. Measurements of the wetting and drying phases at 50°C were completed. Measurements of the wetting phase have begun at 25°C. New samples from the ESF have been prepared, and measurements on these samples at 25°C will begin when porosity is determined. Results of this work will be used to develop moisture retention curves needed by models such as V-TOUGH and NUFT to predict the hydrothermal environment of the waste package.

Activity 1.10.4.2.5 - Model validation experiments. The objectives of this activity are to develop and conduct laboratory tests for model validation and hypothesis testing that provide the basis for confidence building for coupled thermal-hydrological-geomechanical-geochemical process models required for total system performance assessment. The experiments will test the adequacy of the models to represent coupled thermal-hydrological-geomechanical-geochemical flow and transport processes at Yucca Mountain that significantly affect waste package performance, radionuclide release, and radionuclide transport.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.2.6 - Model development and analysis of thermal-hydrological flow and transport. The objectives of this activity are to conduct modeling studies for the range of potential repository thermal loading options and for the thermal loading cycle to

1. Identify coupled thermal-hydrological-geomechanical-geochemical processes, transport processes, and ambient site conditions (e.g., bulk permeability distribution) that significantly affect the waste package and engineered barrier system environment (i.e., those that affect waste package performance and radionuclide dissolution, release, and transport). The effect of these processes and conditions on temperature, relative humidity, and flow conditions throughout the repository and engineered barrier system will be emphasized.

2. Determine the parameter sensitivity of the thermal-hydrological behavior in the near field and engineered barrier system to a range of expected site conditions, waste package designs, repository configurations, waste package loading scenarios, and repository operational options (e.g., ventilation and backfill). Of particular importance are dryout and rewetting behavior.
3. Develop mathematical and numerical models of repository-heat-driven flow and radionuclide transport, emphasizing the waste package and engineered barrier system environment. These models should be capable of treating the importance of coupled thermal-hydrological-geomechanical-geochemical and transport processes in the thermally altered zone. These processes include (a) nonequilibrium fracture-matrix interaction, (b) coupled reactive transport, (c) coupled fracture-aperture deformation, and (d) heat-altered thermal and hydrological flow and transport properties.
4. Establish hypotheses critical to predicting thermal-hydrological behavior and engineered barrier system performance. Design laboratory- and field-scale experiments that test these hypotheses.
5. Develop validated subsystem models of the waste package and engineered barrier system environment. The experiments of Activity 1.10.4.2.5 will be used, in part, to validate the models.

The following paragraphs summarize progress made this reporting period on this activity.

Near-Field and Altered Zone Thermal-Hydrology

Drift-scale and hybrid drift-scale mountain-scale analyses of the thermal-hydrological behavior in the near-field environment, the engineered barrier system, and the altered zone continued this reporting period. Much of this work involved the use of two new three-dimensional, multiple-waste package models, which are based on the NUFT code, including a drift-scale version and a hybrid drift-scale mountain-scale version. These models represent six waste packages, which each have unique decay heat characteristics. The three-dimensional drift-scale model represents detailed three-dimensional thermal-hydrological behavior in and around the emplacement drifts and one-dimensional mountain-scale thermal-hydrological behavior that occurs from the water table to the ground surface. The hybrid model represents detailed three-dimensional thermal-hydrological behavior in and around the drifts and three-dimensional mountain-scale thermal-hydrological behavior from 1 km below the water table to the ground surface. Use of the two models provides the ability to represent emplacement drift behavior over the range of repository locations and time periods of interest. Information from the use of these models and information from past thermal-hydrological modeling studies have been synthesized as part of the process of developing Revision 1 to the Near-Field and Altered Zone Environment Report, completed this reporting period.

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Waste Package Layout Effects

Section 5.2.1 of this progress report discusses sensitivity studies related to waste package layout. The discussion that follows provides details on work that has addressed the thermal hydrological processes and thereby has supported those sensitivity studies.

Modeling efforts this reporting period focused on the following:

1. The influence of heat generation variability among waste packages on thermal-hydrological conditions in emplacement drifts and in the near-field rock was analyzed for alternative waste package layouts.
2. The influence of higher percolation flux (up to 5 mm/yr) on thermal-hydrological conditions in emplacement drifts and in the near-field rock was analyzed for alternative waste package layouts.

The following key observations resulted from this work:

1. Three-dimensional models that discretely represent heat generation from multiple waste packages are required to adequately represent the distribution of temperature, relative humidity, liquid saturation, and liquid-phase flux in and around emplacement drifts. Models that average the waste package decay heat distribution into either a uniform planar heat source or a uniform line-heat source can give a distorted impression of the distribution of temperature, relative humidity, liquid saturation, and liquid-phase flux in and around emplacement drifts. Models that smear out the heat generation distribution tend to yield results that are representative of average rock conditions; however, significant deviations from average conditions would occur, depending on the waste package layout and the location of interest (e.g., the drift wall versus a mid-pillar location).
2. Higher percolation fluxes (above 1-5 mm/yr) would significantly suppress the spatial and temporal extent of rock dryout and the reduction in relative humidity associated with that dryout.
3. For the same overall areal mass loading (83.4 MTU/acre), differences in the waste package layout would result in a markedly different outcome with respect to the distribution of temperature, relative humidity, liquid saturation, and liquid-phase flux on the respective waste packages and along the emplacement drifts.
4. Rock dryout along emplacement drifts would be much more intensive (and uniform) for the line-load waste package spacing (waste packages placed nearly end to end) compared with the square waste package spacing in the advanced conceptual design. Consequently, during the time that decay heat would dominate liquid-phase flow near the repository, the line-load design would result in lower relative humidity and much lower liquid-phase flux near waste packages than would the advanced conceptual design layout.

5. Higher maximum peak temperatures (approximately 20 to 30°C higher) would occur in the emplacement drifts for the line-load design as compared with the advanced conceptual design. It is important for total system performance assessment to assess the consequences of the higher temperatures in line-load design versus the consequences of the higher relative humidity and higher liquid-phase flux in emplacement drifts in the advanced conceptual design layout.

There has been considerable discussion about the advantages and disadvantages of various thermal loading strategies, with much of the debate focused on the areal mass loading (MTU/acre). While there are many competing factors (e.g., operational constraints, costs, and material responses) to consider in evaluating the impacts of alternative thermal designs, some of the key considerations involve the dominant role that decay heat would play in determining the thermal-hydrological conditions in and around the emplacement drifts and, in particular, on the waste package itself. A key consideration for nuclear waste isolation is when and how water would contact a waste package, thereby affecting waste package integrity, and if waste packages are breached, waste form dissolution and release from the waste packages. The manner in which decay heat would influence the distribution of liquid saturation and liquid-phase flux within the drifts (or the engineered barrier system) would strongly affect radionuclide transport within and eventual radionuclide release from the engineered barrier system. The manner in which decay heat would influence the distribution of liquid saturation and liquid-phase flux in the near field and altered zone would affect radionuclide transport within those zones. The thermal-hydrological effects of decay heat would influence geomechanical and geochemical changes in the near field and altered zone (as a result of coupled thermal-hydrological-geomechanical-geochemical processes), which could also affect thermal-hydrological flow and radionuclide transport within those zones. Effects of coupled thermal-hydrological-geomechanical-geochemical processes would continue to influence radionuclide transport well after decay heat has stopped mobilizing gas-phase and liquid-phase flow in the unsaturated zone.

One of the most important conclusions obtained from the use of the three-dimensional multiple-waste package models is that the details of how the waste packages would be configured within the repository (e.g., in a square configuration versus a line-load configuration with tight axial waste package spacing and wide drift spacing) would play a much greater role in determining whether near-field thermal-hydrological behavior is beneficial or deleterious than would the overall areal mass loading of the repository itself. One of the primary objectives of drift-scale and hybrid drift-scale mountain-scale analyses is to establish functional relationships (i.e., the parametric sensitivity) between repository system parameters and near-field thermal-hydrological behavior, and thereby help develop a quantitative framework upon which thermal management principles may be incorporated into the design of the repository system. These functional relationships are also needed to (a) provide guidance for thermal-hydrological testing, (b) assist in the model abstraction process for total system performance assessment, and (c) provide a quantitative framework for comparing various alternatives that are being evaluated by the systems studies.

Mechanisms for Water Contacting a Waste Package

Water may contact a waste package either through liquid-phase (advective or diffusive) flow or condensation of water vapor that forms a liquid film on the waste package. There are three ways by which this contact may arise:

Drift seepage. Advective liquid-phase flow of water that enters the drift (and flows through the backfill if present) as a result of ambient percolation or decay heat-driven condensate flow. This can include episodic nonequilibrium fracture flow or a steady weep.

Wicking. Wicking is the transport of moisture driven by matrix potential gradients (i.e., capillary pressure gradients). This is primarily considered to be an advective liquid-phase transport process (called imbibition); however, binary gas-phase diffusion can also play a role. Because wicking can occur as two-phase flow, it does not necessarily require a continuous liquid phase.

Cold-trap effect. Axial vapor flow and condensation within the drift is driven by axial variations in temperature and vapor pressure along the drift. Water vapor is transported (by gas-phase advection and diffusion) from areas of higher temperature and vapor pressure to areas of lower temperature and vapor pressure where it condenses, which causes relative humidity to increase (even as high as 100 percent). Large condensation rates can arise in the cooler areas if the following three conditions are met: (1) high relative humidity in the rock at the drift wall, (2) waste package heat output varies substantially from waste package to waste package, and (3) waste packages are thermally isolated from one another. The percentage of waste packages that may experience relative humidity of 100 percent and cold-trap-effect-driven condensate fluxes increases with decreasing areal mass loading or with proximity to the edge of the repository. This mechanism can occur whether or not any liquid water seeps into the drift.

For all three of these effects, the most important thermal-management design factor is the waste package layout rather than the overall areal mass loading of the repository itself.

Liquid-Phase Flux Entry into Drifts

Liquid-phase flux may enter a drift as the result of ambient percolation flux and decay-heat-mobilized vapor and condensate flow. A key question is whether (or under what conditions) decay heat would decrease or increase the magnitude (or probability) of liquid-phase flux entering a drift. Depending on the areal mass loading, decay heat would be capable of generating a zone of counter-current two-phase flow above the repository, which is sometimes called the refluxing zone or the heat-pipe zone (Nitao, 1988; Pruess et al., 1990; and Buscheck and Nitao, 1994); this zone would experience liquid-phase fluxes that are much larger than ambient. If the areal mass loading is high enough, this zone could be displaced well above the repository horizon by the superheated (above-boiling-temperature) zone. If either the areal mass loading is not large enough or the ambient percolation flux is too large, it would be possible for the heat-pipe zone to remain at the repository horizon. A heterogeneous permeability distribution could also cause the heat-pipe zone to remain at the repository horizon in regions where condensate flow is focused. The fundamental relationship is between the local heat flux and the heat flux required to vaporize the incoming local

liquid-phase flux. Theoretical studies of the effect of decay heat on condensate flux (Nitao and Bradford, 1996) showed that the tendency for hot and dry conditions to prevail (rather than hot and wet conditions) would depend on whether there would be enough heat flux locally that would be capable of evaporating the local liquid-phase flux. The local heat flux q_H (which, during the initial heat-up period is proportional to lineal mass loading; thereafter it is proportional to areal mass loading) would prevail over the local liquid-phase flux q_{liq} (of ambient and mobilized water) if the following holds:

$$q_H > q_{liq} \rho_{liq} h_{fg} ,$$

where ρ_{liq} is the mass density of water and h_{fg} is the latent heat of vaporization. If there is too much liquid-phase flux, then there would be insufficient heat flux to generate superheated conditions at the repository horizon.

A key question concerns whether heterogeneity in the natural system and/or engineered system parameters that govern the distribution of liquid-phase flux could focus enough liquid-phase flux (at least) locally to overcome the heat flow. In addition to affecting the distribution of liquid-phase flux, heterogeneity in the natural system and/or engineered system parameters could also cause the temperature and relative humidity on the respective waste packages to vary substantially along the drift.

Waste package arrangement would have a fundamental effect on the issue of liquid-phase flux vs. heat flow. The advanced conceptual design used a "square" spacing that would attempt to uniformly distribute the waste package decay heat over the repository area by placing the waste packages with roughly the same axial and lateral spacing between waste packages. The alternative, line-load approach would lineally concentrate waste package decay heat to a much greater extent by placing the waste packages nearly end to end along the emplacement drifts. For a given areal mass loading, this arrangement would allow for greater spacing between drifts and would require smaller total length of emplacement drift.

The advanced conceptual design would have a lineal mass loading of 0.46 MTU/m and drift spacing of 22.5 m at an areal mass loading of 83 MTU/acre. Heating heterogeneity that would arise from square waste package spacing would add substantially to the effects of natural system heterogeneity on the spatial variability of temperature, relative humidity, liquid-phase saturation, and liquid-phase flux along emplacement drifts. On the other hand, for the same areal mass loading a line load case using for example a 0.1-m gap between waste packages would result in lineal mass loading of 1.11 MTU/m (assuming 30 percent of waste packages contain defense high-level waste) and drift spacing of 53.8 m. In spite of the large differences in heat generation among the various waste packages, the highly efficient thermal-radiative waste package-to-waste package heat transfer facilitated by the end-to-end waste package spacing would cause the line of waste packages to function as a more uniform line-heat load. Consequently, the line-load is predicted to generate more uniform temperature, relative humidity, liquid saturation, and liquid-phase flux along the drifts. Moreover, the high axial waste package-to-waste package heat conductance would homogenize some of the effects of natural system heterogeneity and edge-cooling/

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rewetting/shedding on conditions along the drift. In effect, the line of closely spaced waste packages would serve as a preferential heat-flow conduit that would allow heat to be delivered to otherwise cooler areas of the drift.

For the line-load design just described, lineal mass loading would be 2.4 times greater than in the advanced conceptual design; consequently, the local heat flux near the drifts would be 2.4 times greater, which would result in much more locally intensive rock dryout for the line-load design than for the advanced conceptual design. The net effect of more uniform and more intensive local heat flux along the drifts would be that relative humidity in the rock (and on waste packages) would be drier and more uniform for the line-load design than for advanced conceptual design. Moreover, the liquid-phase flux above the drift is predicted to be very small for the line-load design for 4000 years, whereas for the advanced conceptual design, the liquid-phase flux above the drift would be much greater than ambient. (For times up to 500 years, liquid phase flux would be 100 to 400 mm/yr; for 500 to 2000 years, it would be 10 to 100 mm/yr.) For the no-backfill case, the coolest and most humid waste package in the line-load design would be drier than the hottest and least humid waste package in the advanced conceptual design.

The line-load design would achieve the somewhat drier conditions at the cost of higher maximum peak temperatures (approximately 30 to 50°C higher) on waste package and drift surfaces than would occur in the advanced conceptual design. The maximum peak temperature would occur near waste packages containing 21 design basis pressurized water reactor fuel assemblies. It is important for total system performance assessment to compare the consequences of the higher waste package and drift-wall temperatures in the line-load design with the consequences of the higher relative humidity and higher liquid-phase fluxes on waste packages in the advanced conceptual design.

Drift- ΔRH Effect

A key attribute of the engineered barrier system, affecting its ability to contribute to waste isolation, is the degree to which it causes a relative humidity difference (ΔRH_{drift}) between the hotter (and drier) waste package and the cooler (and more humid) rock at the drift wall. The drift- ΔRH effect is quantified by the relationship

$$RH_{\text{wp}}/RH_{\text{dw}} = P_{\text{sat}}(T_{\text{dw}})/P_{\text{sat}}(T_{\text{wp}})$$

where:

RH_{wp} is relative humidity at the waste package surface

RH_{dw} is relative humidity at the drift wall

$P_{\text{sat}}(T_{\text{dw}})$ is saturation pressure of water at the drift wall temperature

$P_{\text{sat}}(T_{\text{wp}})$ is saturation pressure of water at the waste package temperature.

This relationship depends primarily on the temperature difference (ΔT_{drift}) between the waste package and drift wall. Therefore, the heat transfer attributes of the engineered barrier system are key in determining the extent to which relative humidity can be reduced on the waste package. Of particular significance is whether a low thermal conductivity backfill should be used to insulate the waste package from the drift wall. Use of such material would generate a much larger ΔT_{drift} than would occur if the drift remains open. In an open drift, thermal radiation would be the primary mode of heat transfer between the waste package and the drift wall.

During the drift-scale modeling work, the major heat transfer attributes of the engineered barrier system that determine ΔT_{drift} were determined. Much of the parameter sensitivity analyses were structured by examining these major heat-transfer attributes. The following key findings were made:

Decay heat distribution in the emplacement drift. This parameter, as previously stated, would be primarily affected by the waste package heat generation distribution and axial waste package spacing, which together would determine the amount of decay heat generated per unit length of drift and how efficiently heat is transferred by thermal radiation from waste package to waste package. The efficiency (or lack thereof) of heat transfer from waste package to waste package would strongly affect the variability of the heat flux distribution on the drift wall and floor surfaces, which in turn would affect the temperature distribution along the drift surfaces. Large axial waste package spacing (as in the advanced conceptual design) would cause the waste packages to be thermally isolated from one another, which would result in large variability (in the axial direction) in temperature, relative humidity, liquid saturation, and liquid-phase flux on the respective waste packages and in the near-field rock. Close waste package spacing (as would occur in the line-load design) would result in good thermal communication between the waste packages, which would result in more uniform temperature, relative humidity, liquid saturation, and liquid-phase flux on the respective waste packages and in the near-field rock. The higher local heat flux for the line-load design would also result in much lower liquid-phase flux near the respective waste packages than would the advanced conceptual design.

Waste package emissivity. This parameter indicates how efficiently heat is transferred by thermal radiation between a waste package and (a) the drift floor, (b) the drift wall, and (c) adjacent waste packages. For cases without backfill, the waste package emissivity, along with the heat flux from the waste package, would determine ΔT_{drift} , which would determine the maximum possible ΔRH_{drift} .

Thermal properties of the emplacement drift. The key attributes are (a) drift diameter, (b) thermal conductivity of the invert, (c) thermal conductivity of the backfill (if used), and (d) the percentage of the drift occupied by the invert and backfill. Together, these attributes would determine how well the waste packages would be insulated from the near-field rock. A low thermal conductivity backfill would effectively function like a thermal blanket that would significantly increase ΔT_{drift} , which in turn would increase ΔRH_{drift} . Drift diameter would influence thermal-radiative heat transfer within the drift. Peak waste package temperatures and the variability in heat flux distribution along the drift surfaces would decrease with increasing drift diameter.

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In addition to the heat-transfer attributes of the engineered barrier system, the key hydrological attributes of the engineered barrier system and natural system that would affect ΔRH_{drift} were identified, and their influence on relative humidity reduction was assessed. The attributes were as follows:

Hydrological properties of the emplacement drift. The hydrological properties of the invert and backfill (if used) would affect the degree to which wicking may transport moisture from the (cooler and more humid) near-field rock to the (hotter and less humid) waste package surface. If wicking in the invert or backfill is present, it could reduce ΔRH_{drift} . The bulk permeability of the backfill would determine the degree to which buoyant gas-phase convection would influence heat transfer between the waste package and drift wall. The hydrological properties of the backfill and invert would also help determine how effectively the drift seepage flux is able to drain out of the drift.

Ambient percolation flux. This quantity, which is the liquid-phase flux in the host rock (the TSw2 unit), is the net result of infiltration and exfiltration and the ability of the Paintbrush nonwelded hydrogeologic unit to divert the net infiltration flux that reaches the Paintbrush nonwelded hydrogeologic unit. The temporal nature of percolation flux can range from episodic flow in fractures to steady-state flow in both the fractures and the matrix. Imbibition in the Paintbrush nonwelded hydrogeologic unit serves to dampen the influence of episodic infiltration events and thereby provides more time for exfiltration and lateral flow to influence the moisture balance in the Paintbrush nonwelded hydrogeologic unit; all of which tend to reduce the percolation flux in the TSw2. The ambient percolation flux at the proposed repository horizon would affect the potential drift seepage flux, particularly when decay heat would no longer dominate the liquid-phase flow distribution at the repository horizon. For the 83.4-MTU/acre advanced conceptual design, heating heterogeneity and less intensive rock dryout near the emplacement drifts (than in the line-load design) would cause liquid-phase flux to be much greater than ambient in the vicinity of emplacement drifts during the decay-heat-dominated regime (0 to 3000 years), while the greater rock dryout in the vicinity of the line-load drifts would cause liquid-phase flux in the vicinity of the drifts to be very small during the decay-heat-dominated regime.

Ambient liquid saturation distribution. For conditions relevant to Yucca Mountain, this quantity can be no less than what is caused by gravity-capillary-pressure equilibrium with the water table. Liquid saturation increases with decreasing height above the water table (or perched water body). Liquid saturation also increases with percolation flux, particularly if that flux is steady. Matrix potential increases with liquid saturation. Because wicking in the invert and backfill depends on the matrix potential in the adjacent rock, the possibility of wicking increases with liquid saturation.

Proximity to the edge of the repository. Of particular concern is the edge-shedding effect, which can substantially increase the liquid-phase flux at the edge of the repository as compared with conditions at the center of the repository (or as compared with ambient conditions).

Assessment of Thermal-Hydrological Models

The capabilities and limitations of three major types of thermal-hydrological models were assessed:

1. Mountain-scale model. To account for the variable overburden thickness and to account for the details of the hydrostratigraphy, a three-dimensional model is required to accurately account for the following important quantities:

Average temperatures in the repository rock. The influence of the edge-cooling effect on the temporal and spatial distribution of average temperature in the repository rock.

Average relative humidity in the repository rock. The influence of the effects of edge-cooling, edge-rewetting, and edge-shedding on the temporal and spatial distribution of average relative humidity conditions in the repository rock.

2. Drift-scale model. To account for the heat generation variability from waste package to waste package, a three-dimensional model is required to accurately account for the following important quantities:

Temperature difference between the waste package and the drift wall. This quantity (ΔT_{drift}) is independent of areal mass loading (and proximity to the repository edge); therefore, ΔT_{drift} can be accurately predicted with the drift-scale model.

Temperature and relative humidity difference between the pillar centerline and the drift wall. These quantities (ΔT_{pillar} and $\Delta RH_{\text{pillar}}$) depend on areal mass loading and drift spacing. If the effective areal mass loading (and drift spacing) are accounted for appropriately in the drift-scale model, then ΔT_{pillar} can be accurately represented with the drift-scale model.

3. Drift-scale and mountain-scale models. Ideally, a three-dimensional thermal-hydrological model will be used to incorporate both drift-scale and mountain-scale thermal-hydrological behavior. Such a model will, however, be extremely computationally expensive to run, thereby making it very difficult to conduct sensitivity studies. During this review period, a hybrid drift-scale/mountain-scale model was developed that involves a model abstraction process that combines the results from drift-scale and mountain-scale thermal-hydrological models. This abstraction process uses three steps for calculating the temperature at selected repository locations and selected waste package locations.

Step T-1: Average rock temperature at selected repository locations. Using a mountain-scale model, temperatures which are representative of the average temperature in the rock are obtained at selected repository locations.

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Step T-2: Drift-wall temperature at selected repository and waste package locations.

This temperature is determined by taking temperature from step T-1, and adding one-half of ΔT_{pillar} determined from the drift-scale model for each of the selected waste package locations. Half of ΔT_{pillar} is used (rather than 100 percent) because ΔT_{pillar} is the temperature difference from the coolest portion of the rock pillar (i.e., the centerline) and the hottest portion of the rock pillar (i.e., the drift wall). The mountain-scale-model temperature is representative of the average rock pillar temperature (not the coolest rock pillar temperature).

Step T-3: Waste package temperature at selected repository and waste package locations.

This temperature is determined by taking temperature from step T-2 and adding ΔT_{drift} determined from the drift-scale model for each of the selected waste package locations.

The abstraction process also uses three steps for calculating relative humidity at selected repository locations and selected waste package locations:

Step RH-1: Average rock relative humidity at selected repository locations.

Using a mountain-scale model, relative humidities which are representative of the average relative humidity in the rock are obtained at selected repository locations.

Step RH-2: Drift-wall relative humidity at selected repository and WP locations.

This relative humidity is determined by taking relative humidity from step RH-1 and adding one-half of $\Delta RH_{\text{pillar}}$ determined from the drift-scale model for each of the selected waste package locations. Half of $\Delta RH_{\text{pillar}}$ is used (rather than 100 percent) because $\Delta RH_{\text{pillar}}$ is the relative humidity difference from the most humid portion of the rock pillar (i.e., the centerline) and the least humid portion of the rock pillar (i.e., the drift wall). The mountain-scale-model relative humidity is representative of the average rock pillar relative humidity (not the most humid rock pillar relative humidity).

Step RH-3: Waste package relative humidity at selected repository and waste package locations.

This relative humidity is determined by taking relative humidity from step RH-2 and multiplying it by the ratio $P_{\text{sat}}(T_{\text{dw}})/P_{\text{sat}}(T_{\text{wp}})$, where $P_{\text{sat}}(T)$ (saturation pressure) is determined from the steam tables, for each of the selected waste package locations. The temperature at the drift wall T_{dw} is determined in step T-2; the temperature on the surface of the waste package T_{wp} is determined in step T-3.

This thermal-hydrological model abstraction process can be applied to combine the results of detailed three-dimensional multiple-waste package drift-scale models with those of three-dimensional mountain-scale models.

Forecast: The electrical properties measurements as a function of temperature and saturation will be improved at high temperature by use of a new sample holder that will help maintain constant saturation levels. Measurements at low temperature will be improved through the use of a better climate control system that will minimize temperature variations. A new

dielectric measurement fixture has been obtained and will enable better, higher frequency measurements of the dielectric constant. The measurement of characteristic curves at elevated temperature will continue on previously used samples to permit an evaluation of the effect of sample history (thermal cycling and saturation/de-saturation) on the measured properties. Measurements on the new samples, combined with data from the single-heater test, will be used to construct better models of coupled thermal-hydrological properties.

Modeling work will focus on developing the ability to more accurately account for (a) spatially variable ambient percolation flux distributions, (b) fracture-matrix interaction, and (c) spatially variable natural system properties such as bulk permeability in the drift-scale and hybrid drift-scale/mountain-scale thermal-hydrological models. A major goal of this effort is to develop the ability to more accurately predict seepage flux distributions along emplacement drifts. The thermal-hydrological modeling effort will be closely coordinated with site-scale thermal-hydrological modeling activities and with altered zone activities. There will also be increased effort in parameterizing drift-scale thermal-hydrological behavior to assist in model abstractions required by total system performance assessment activities in support of the 1998 viability assessment.

5.2.4 Study 1.10.4.3 - Characterization of the Geomechanical Attributes of the Waste Package Environment

The objective of this task is to characterize the geomechanical response of the rock in the near field to the changing conditions expected to occur over the lifetime of the repository. This includes providing data from laboratory, field, and modeling investigations that can be used to support evaluations of the suitability of the site and to support licensing. Particular emphasis is on coupled processes and behavior at elevated temperatures and at long times.

This study had one activity in the SCP. When the study plan was written, the material was reorganized into three activities. The description of the original activity is included in Appendix A of this progress report. The status of the current activities is provided below.

Activity 1.10.4.3.1 - Block stability analysis. The objective of this activity is to identify and understand how the transport, physical, and mechanical properties of the near-field region are affected by thermal-mechanical behavior over time. This includes developing and applying constitutive models and numerical codes for analysis of geomechanical influences on the behavior of rock in the near-field environment over time. Analytic and numerical methods include continuum and statistical methods. Particular emphasis will be on the development and implementation of techniques for coupling of geomechanical with geochemical and hydrologic codes. Emphasis will also be placed on modification of existing codes as necessary to enhance the analysis of the field testing activities, and if appropriate, the integration of the geomechanical behavior into the performance assessment modeling of the site.

During this reporting period, coupled three-dimensional modeling of thermal-mechanical-hydrologic behavior of the proposed repository was initiated. The purpose of this modeling is to

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evaluate the effect of thermal-mechanical deformation over time on the hydrologic behavior of the proposed repository. The first step was to use thermal-hydrologic models to compute a temperature distribution for the particular problem being simulated. This temperature field is then passed to the thermal-mechanical model for the computation of stress and deformation fields. The thermal-mechanical model is set up with the same grid as the thermal-hydrologic model. The particular codes being used are NUFT for the thermal-hydrologic behavior, and three-dimensional FLAC for the thermal-mechanical behavior. Progress to date includes the completion of the translating program that passes the NUFT grid into FLAC and initial testing of the mechanical behavior using this grid.

A series of two-dimensional simulations of the drift-scale test was also performed using the two-dimensional version of the FLAC model. The purpose of these simulations was to estimate stress and deformation fields as a function of time in the rock mass being heated. The process began with modeling the rock as a purely elastic material, and then displacements and stresses from heating were computed. In these calculations, a vertical cross-section perpendicular to the long axis of the canister heaters and heated drift was simulated. The main result of this modeling was that the region about 1 m from the heated drift wall would reach about 200°C in 200 days of heating. The elastic analysis provides a conservative (bounding) estimate of the stress and displacement fields. For this simulation, stresses at the drift wall were estimated to be about 70 MPa, which is about one half the value of the matrix compressive strength of the rock. Displacements near the drift wall were estimated to be on the order of a few millimeters after 200 days.

The FLAC code was then used to model the effects of fractures on the displacements and stresses over time in the drift-scale test. The model contained one vertical interface and one horizontal interface to represent two fractures in cross section. The main differences in results for the fracture model when compared with the homogeneous model are that with the fracture model the horizontal and vertical stresses near the fractures are about 10 MPa lower, and the displacements are concentrated along the fractures for the model having fractures. This result is important because it provides an estimate of the amount of stress reduction in the rock that can be expected due to the presence of fractures.

Although possible, it is not particularly easy or convenient to compare results of earlier FLAC geomechanical modeling described previously to the hydrology modeling results of Buscheck and Nitao (1995). Therefore, the geomechanical models were reconfigured to allow a more direct comparison with the hydrologic simulations. Good agreement was found between the thermal-hydrology results and the FLAC temperature results, which indicates that stress and displacement results calculated using FLAC can be related to the hydrology models for simulations of both the single-heater test and the drift-scale test. The agreement also shows that the FLAC model is properly representing the heaters. These results are useful because they provide confidence that thermal-mechanical and thermal-hydrologic estimates can be used in concert to assess the rock response to heat.

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Activity 1.10.4.3.2 - Borehole damage analysis. The objective of this activity is to provide information on the potential for static loads on the waste package and for radionuclide releases caused by spalling or breakup of the wall of the emplacement drift or borehole.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.3.3 - Geomechanical properties analysis. The purpose of this activity is to perform experimental investigations of the coupled thermal-mechanical, thermal-hydrological, and thermal-chemical response of the rock to conditions similar to the near-field environment of the proposed nuclear waste repository. This activity includes testing of 0.5 m scale blocks of tuff. Data at this scale are needed to provide input to models used for analysis of the repository because very few data sets are available from in situ rock masses and data from smaller samples commonly tested in the laboratory do not provide information on fracture behavior. Moreover, in tests at this scale known boundary and environmental conditions can be imposed on a rock sample that contains multiple fractures; field data are often poorly constrained because of inherent limitations on boundary conditions, sampling intervals, and material characterization.

Rock Mass Testing

During the reporting period, data from the first thermal-mechanical test on a block at 0.5 m scale were analyzed. In addition, the second in a series of laboratory compression tests on 0.5-m-scale blocks of Topopah Spring Tuff was set up. These tests are designed to measure the effect of compressive stress and temperature on liquid flow in a single fracture.

Results indicate (a) that most deformation occurred in vuggy zones (zones containing holes formed during deposition of the tuff) and along fractures, and (b) that the matrix material is an order of magnitude stiffer than the 0.5-m fractured rock sample, which is in turn an order of magnitude stiffer than an individual fracture. These data also indicate that cyclic loading at low stress may cause subcritical crack growth (growth of cracks at stress levels lower than that required for fracture). These results indicate constraints on how the flow and transport properties of the rock in the very near-field region of a repository may change as the temperature and stress fields change over time.

Results at elevated temperature indicate that some deformation occurred at constant stress while the sample was heated to and held at temperature, and that the deformation modulus decreases as temperature is increased. A weak but consistent correlation between the elastic wave velocities and temperature was noted. The results also led to postulation that high temperatures help to close and heal cracks and thus are related to high wave velocities. Results of the first test conducted on 0.5-m blocks were presented by Blair and Berge (1996) at the 1996 High-Level Waste Conference. These results are important because crack healing and closure may improve the site's ability to restrict radionuclide release by decreasing permeability in the near field.

Support of the Single-Heater Test in the ESF

A reflective optical extensometer system was developed to measure distance and displacements in the emplacement drifts and boreholes. This method is inherently insensitive to temperature and other environmental effects that may be encountered in the potential repository, so data collected using this instrument will require fewer corrections than data collected using conventional extensometer systems. In this design, reflecting targets are placed at desired measurement locations such as at various depths in a borehole or at selected locations along a drift wall, and the distance between each target and an optical head is measured repeatedly using a modulated laser beam. The system is inherently reliable because all electronic and moving parts are located outside of the high temperature, or otherwise hostile environment. Also, the optical head is connected to the laser, switching, and signal analysis hardware using optical fibers. Because the signal is transmitted over optical cables, electrical noise and resistance are eliminated. A reference beam is used to provide direct correction of system behavior. This system can be used to measure distances from a few centimeters to several tens of meters.

The system was implemented in two boreholes associated with the single-heater test. One of the holes is oriented parallel to the heater and the other is oriented perpendicular to the heater. Retrievable reflective targets are being used in this application for quick and easy installation, relocation, or removal from a borehole.

Forecast: During the next reporting period, work on block stability analysis will focus on evaluating available methods for estimating changes in fracture permeability surrounding drifts in the ESF and repository in response to construction-induced stress changes, and subsequently in response to the thermal pulse arising from waste emplacement. These results are needed for modeling changes in repository-level moisture movement. Selected techniques will also be used to estimate bounds on the changes in permeability of the host rock resulting from drift excavation and from thermo-mechanical stresses. Experimental data and data from the ESF will be used as they become available. To the extent possible, correlations will be made with matrix rock properties, fracture patterns, or other parameters readily measured in the ESF or the laboratory and available from other activities.

Block stability analysis work will also include analysis of deformation data from the single-heater test and simulation of the drift-scale test in both two and three dimensions for the purpose of assessing the performance of the thermal-mechanical models. In addition, a statistical model will be developed and applied to simulate crack formation and growth at elevated temperatures. Future FLAC modeling will also test the effects of changing the thermal properties used for the backfill material.

Support of the single-heater test will include continued monitoring of rock deformation using the current reflective optical extensometer instrument. A second-generation reflective optical extensometer instrument with improved performance will be built and installed. An external review of the reflective optical extensometer instrument will be held in mid-November 1996.

Rock mass testing will include performing laboratory experiments on 0.5-m-scale blocks of Topopah Spring Tuff to obtain data on coupled thermal-hydrological-mechanical-chemical processes in a rock specimen containing multiple fractures. These experiments will provide data on the effect of temperature and stress on fracture permeability and on the coupled processes occurring in the fractured rock at temperatures in the range 90 to 250°C. These tests coupled with the single-heater test now under way in the ESF will provide the only experimental data (prior to the total system performance assessment that will support the viability assessment) on nonisothermal flow at a scale large enough to include multiple fractures. These 0.5 m scale laboratory tests also allow investigation of the effects of thermal and mechanical stresses on flow, providing a degree of test control that is not achievable in situ. The results will be essential for constraining models of near-field coupled processes that support total system performance assessment and waste package design. Moreover, data from these experiments will help determine pre- and postclosure rock characteristics for models of pre- and postclosure repository performance. Data will also be used in the design and interpretation of the drift-scale test now being constructed.

The first test will begin on the sample that was set up during this reporting period. Compressive stresses up to 15 MPa and temperatures up to 110°C are planned to investigate the scale dependence of geomechanical properties. These tests are the first of a series of tests designed to study coupled processes in the near-field environment of a nuclear waste repository. Results will provide new deformation and flow data for a sample containing a single, through-going fracture.

5.2.5 Study 1.10.4.4 - Engineered Barrier System Field Tests

The laboratory tests described in Studies 1.10.4.1 through 1.10.4.3 (Section 5.2.2 through 5.2.4 of this progress report) require validation by in situ field tests in the repository horizon to establish the applicability of the laboratory studies to the repository block. The objective of this study is to investigate the geomechanical and geochemical behavior and movement of water in the rock mass under the influence of the thermal loading of the waste package. The study will investigate heat-flow mechanisms, fracture aperture change, geochemical reactions, the relationship between boiling and dryout, and the rewetting of the dryout region when the repository is cooled down. Coupling between heat, hydrology, geomechanics, and geochemistry will be included in the study. These activities will test some of the coupled processes that will be part of the models the Project plans to use to predict the repository near-field environment.

This study had three activities in the SCP. When the study plan was written and subsequently revised, the material was organized differently than in the SCP. The cross linkage of the original activity descriptions to the current activities is included in Appendix A of this progress report. The status of the current activities is provided below.

Activity 1.10.4.4.1 - Sampling and sample analyses. The objective of this activity is to collect and analyze material samples (rock, gas, and water) before, during, and after heating of the

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rock as field testing occurs. The laboratory analyses of the samples will determine hydrologic and geochemical properties of the rock and chemistry of the gas and water.

Cores resulting from the installation of the single-heater test have been obtained for mineralogical and petrological analyses. The analyses have begun, and the results will be reported by the end of FY 1997.

Activity 1.10.4.4.2 - In situ testing. The objectives of this activity are to develop detailed planning documents for the engineered barrier system field tests and analysis, to check out and debug techniques and hardware, to perform comparative evaluations of candidate test component methods, to procure equipment, to purchase or manufacture test components, to calibrate and install test components, and to conduct in situ testing.

Exploratory Studies Facility Thermal Tests

The ESF thermal tests will be conducted in the Thermal Testing Facility whose construction continued during this reporting period. Two tests are planned: (1) the single-heater test and (2) the drift-scale test using multiple heaters. The Project is considering whether a large-scale long-duration heater test is needed.

Planning for the ESF testing and analysis is occurring as part of a Project-wide effort to consolidate thermal test planning. The Test Design Plans and Layout Report for the ESF Thermal Test document (CRWMS M&O, 1996n) was completed.

The heater and instruments for the single-heater test were installed. Construction of alcove areas for the drift-scale test continued.

Large Block Test

No work was performed for the large block test during this reporting period.

Laboratory Tests for Exploratory Studies Facility Test Design

All the tests discussed here support design of in situ ESF testing. In addition, some results of these tests provide important information in their own right to support analysis of near-field rock properties. In turn, these analyses will be used in repository design and performance assessment.

Matrix Permeability. During the preceding reporting period, a sample was machined from the core sections recovered from the N-1 hole in the large block and was placed in a pressure vessel for measuring gas permeability at high temperatures and various pore pressures. The measurement of gas permeability at various levels of pore pressure to determine the Knudsen diffusion coefficient continued, but results are not yet available.

Fracture Flow Versus Matrix Imbibition. X-ray imaging to determine water saturation in the near-field rock continued. A small block of $2.5 \times 15 \times 30$ cm Topopah Spring Tuff from Fran

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Ridge, with a tensile fracture in the middle, was used to test fracture flow and matrix imbibition against a thermal gradient. This testing began in a previous reporting period and was completed this reporting period. The sample preparation was similar to the previous experiment at room temperature. Three foil heaters were mounted at the bottom of the block. Four thermocouples were mounted along the vertical axis of the block, with the hot junction very close to the fracture surface. The temperature at the bottom of the block was maintained at about 120 to 126°C, and the temperature at the top was about 29°C. Water, doped with potassium iodide to attenuate x-rays, was added to the fracture at the top of the sample, and radiographs were taken as a function of time to try to determine the distribution of water content.

Preliminary results of this testing indicate that fracture flow against a thermal gradient is slower than that at room temperature. In the region of the block below the boiling point, water flowed in the fracture first, before imbibition into the matrix took place. However, water never flowed through the fracture in the boiling zone. Because the proposed repository would experience a significant thermal gradient, actual fracture flow in the repository during the period in which waste heat is significant would likely be lower than in the pre-emplacement rock for a given head of water. This phenomenon could significantly impact repository performance by slowing rewetting of the repository environment. Future experiments will investigate the effect of fracture aperture and infiltration flow rate on the fracture flow vs. matrix imbibition in a heated block.

Relative Humidity as a Function of Saturation. Measurement of relative humidity as a function of moisture content in a Topopah Spring Tuff core continued. The sample preparation and the test procedures were reported in Progress Report #13 (DOE, 1996j). The saturation level at the end of this reporting period was 20 percent, and the measured relative humidity was approaching 97 percent. The relative humidity in the sample is expected to reach 100 percent when the water saturation is increased to about 25 percent. This experiment has demonstrated that even very low moisture content can produce a humid environment in the tuff. This is significant because relative humidity strongly influences waste package material degradation rates. On the basis of these results, very dry host rock would be needed to maintain a low enough relative humidity to retard waste package material degradation. A future test will be conducted at elevated temperatures.

Condensation Along a Fracture. The purpose of these laboratory tests is to simulate conditions predicted to occur in the field, where a dryout zone (associated with the repository thermal load) would exist beneath a condensate zone. Tests similar to those performed last reporting period were performed this reporting period, but with slightly modified parameters. A core sample about 36-cm long and about 5 cm in diameter, with a longitudinal saw cut in the middle, was prepared for the test conducted this reporting period. After mounting gold electrodes along the outer edges of the saw cut and thermocouples along the longitudinal axis of the core (very close to the cut), high-temperature sealant was applied to the surface of the sample as a moisture barrier, and the sample was wrapped with insulation material. Water was added to the dry sample to achieve a moisture content of about 95 percent. The sample was heated from its bottom, while electrical resistance and temperature were measured along its longitudinal (vertical) axis. The temperature at the bottom of the sample was kept at about 167°C, and the temperature at the top stayed at about 33°C. During the heating phase, which lasted for about one week, the

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lower 20 to 25 percent of the sample length was at temperatures above 100°C, and the measured electrical resistance showed the expected effect of temperature and dryout, but no indication of condensation was observed. The temperatures in the sample decreased to room temperature within 24 hours after the heater was turned off, but the electrical resistance did not indicate any re-wetting for several weeks. No vapor was observed in the vapor collection system at the top of the core. However, the weight of the core after the test was completed indicated that most of the water in the core was lost. The results of this test, along with the results from the test performed last reporting period, suggest the failure to detect a condensation zone may be due to loss of water from the experimental system. The moisture barrier will be improved in a future test.

Flow on Fracture Surfaces. An experiment begun last reporting period continued. X-ray scan was used to observe the flow process of water on a real fracture surface. A core of about 15-cm diameter that included a longitudinal fracture was drilled from a small block. A thin slab (2.5 × 15 × 30 cm) of Topopah Spring Tuff with a natural fracture was machined. Water was ponded on top of the slab while the fracture surface was periodically scanned with x-rays. The x-ray images were normalized to enhance analysis of the images. Preliminary test results based on these normalized images will be available in FY 1997.

Fracture Healing. The purpose of these experiments is to determine the effect of confining pressure on fracture healing. This information is necessary to accurately assess whether fracture healing will occur in the repository. If it does, this phenomenon could substantially impede radionuclide transport and therefore improve repository performance. Cores of fractured Topopah Spring Tuff samples are continuing to be machined from the same fracture in a block to support this planned testing. Each core will be used for testing only at one confining pressure and one temperature cycle. The purpose of this procedure is to isolate the effect of confining pressure on the fracture healing. The effect on fracture healing of flowing a finite amount of water at high temperatures through the fracture will also be tested. No test was performed during this reporting period.

Activity 1.10.4.4.3 - Pre- and post-test calculations. The objectives of this activity are to perform scoping calculations in support of engineered barrier system field test design, to develop planning documents, and to reduce and analyze test data. This activity includes the verification and validation process necessary to qualify the numerical methods to be used if not already accomplished by another activity.

Three-dimensional thermal-hydrological model calculations were conducted for the drift-scale test as pre-test calculations. The analyses were conducted for heater drift lengths of 35, 40, and 55 m. Three cases of thermal-hydrological conditions have been studied: conduction only, zero percolation flux, and 0.05 mm per year percolation flux. The peak temperature in the test region at the end of three years of heating is expected to range from 285°C for the 0.05 mm per year percolation rate case to 312°C for the conduction-only case.

Forecast: Some activities forecast to be complete for this reporting period have been delayed because of funding constraints. During the next reporting period, the test design for the drift-scale test will be finalized and the instruments installed. Gas permeability measurements on

the core sample from the large block N-1 hole will be completed. The current fracture flow versus matrix imbibition experiment will be finished, and the test will be redesigned so that a larger dryout region in the sample can be achieved. Relative humidity measurements will continue until the saturation level in the sample reaches 100 percent; then the test will be repeated at elevated temperatures. Condensation along a fracture will be retested with a new moisture barrier on the sample, and electrical resistivity tomography will be used to monitor the moisture distribution. The analysis of x-ray images will continue to determine water flow on fracture surfaces, and experiments will be initiated to study the effects of water flow, temperature, and confining pressure on fracture healing in core samples.

Work on the large block test will resume next reporting period, with installation of heaters scheduled to begin.

5.2.6 Study 1.10.4.5 - Characterize the Effects of Introduced Materials on Water Chemistry in the Postemplacement Environment

The objective of this study is to identify significant chemical modifications of the near-field environment from what would be expected under geological conditions. The modifications would be caused by the construction and operation of the repository. The geological conditions are defined by Study 1.10.4.1 (see Section 5.2.2 of this progress report). In addition to construction materials, a complete picture of the modified chemical and hydrological system includes introduced air and water, the reintroduction of crushed tuff or muck rock, and the introduction of microbial populations.

This study did not exist in the SCP. It was developed from aspects of the near-field geochemistry study (1.10.4.1) which included the effects of introduced materials and radiation from the waste packages. The original organization of the draft study plan included four activities. When the draft study plan was revised, the material was organized differently than in the first draft. To avoid confusion between similarly numbered activities in the initial draft [which was captured in the Site Design and Test Requirements Document (DOE, 1995p)] and the next draft, the current activities were renumbered with higher numbers. The cross linkage of the original activities to the current activities is included in Appendix A of this progress report. The status of the current activities is provided below.

The Introduced (Man-Made) Materials Synthesis Report 1993-1996 (Meike, 1996) was completed this reporting period. Important conclusions from this report are presented in the activities that follow.

Activity 1.10.4.5.5 - Integration: Program Planning; identification, characterization and screening of materials; and bibliographic maintenance and literature review. The objectives of this activity are to prepare planning documents for the introduced materials study, to develop a list of materials that might be used in the repository (including locations, quantities, and concentrations), to develop a chemical data base regarding the materials, to rank the materials on the basis of aggressiveness under expected and certain unexpected repository conditions, to identify materials

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for which information is inadequate, and to gather, synthesize, and evaluate data from the literature. These objectives are not necessarily sequential, and some products will be updated throughout the study.

With the exception of the tracers, fluids, and materials data base, no monitoring or evaluation of materials used in the construction of the ESF is presently being conducted. A previous report (Meike and Spragge, 1995) had determined that the tracers, fluids, and materials data base is not sufficient to obtain the information required for drift-scale hydrological and chemical modeling, so further data will be needed. The introduced materials work, which was directly focused on the support of drift-scale hydrological and chemical modeling, has been canceled because of funding constraints.

Activity 1.10.4.5.6 - Solubility and stability experimental studies at ambient and elevated temperatures. The objective of this activity is to conduct dissolution and precipitation kinetics experiments to determine the sensitivity of the kinetics to temperature and fluid composition. Stoichiometric and nonstoichiometric dissolution of introduced materials, in saturated and unsaturated environments, will be addressed. The experiments are intended to identify the dissolution precipitation mechanisms, the effects of solid solution on rates of dissolution and precipitation, the solid reaction products, and the resulting water chemistry. Solid, liquid, and gas phase stability will be addressed.

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.5.7 - Chemical reactivity stability experimental studies at ambient and elevated temperatures. The objective of this activity is to conduct chemical reactivity experiments on soluble products of introduced solid phases, on introduced organic and inorganic fluids, on introduced material interactions with water and vapor in the presence of a radiation field, on the potential effects of introduced materials on predicted natural chemical reactions, and on the significance of natural mineral moderation (for example, zeolites and buffering effects) on the aggressiveness of introduced materials.

A synthesis of previous work was completed and documented in the Introduced (Man-Made) Materials Synthesis Report. Chemical simulations and analysis were performed in support of the Engineered Barrier System Performance Requirements Systems Study for the chemical composition of interest (chemical modeling of backfill composed of quartz sand, lime, and an iron-bearing mineral phase).

In anticipation of the current interest in concrete, samples of concrete invert material were placed in the single-heater test that has been initiated. This testing will be used to better define changes in concrete materials exposed to temperatures similar to those that would be expected to occur in the proposed repository.

Input is being provided to support performance assessment on the use of precast concrete liners as mechanical support in emplacement drifts.

Exploratory Studies Facility Swipe Test

This part of the activity was not funded in FY 1996, and all new work has ceased. As a result of sampling conducted at the ESF at the end of FY 1995, some results of the extant samples are available in the Introduced (Man-Made) Materials Synthesis Report submitted during this reporting period. A preliminary interpretation of these results suggests that diesel fuel contamination of geologic samples taken from the ESF would result in apparent carbon-14 ages older than the real ages in the samples. Although the extent of such contamination can be determined, this activity is beyond the scope of the preliminary test.

Diesel Fuel Hydrous Pyrolysis

Scoping experiments in this area have been completed, but the publication of the final report continues to be delayed because of funding reductions. It is not known when work in this area will resume.

Activity 1.10.4.5.8 - Colloid stability experimental studies at ambient and elevated temperatures. The objectives of this activity are to identify introduced materials that can produce colloids and to examine the nature and stability of the colloids. This activity is intended to complement other work being conducted in Study 8.3.1.3.5.2 (Section 3.2.11 of this progress report).

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.5.9 - Biodegradation stability experimental studies at ambient and elevated temperatures. The objective of this activity is to identify and characterize microbes that might be introduced into the repository, and microbes (both native and introduced) that derive nourishment from introduced materials that could be brought into the repository. The activity will identify introduced materials that will encourage microbe growth, identify chemical products of microbial degradation, and identify and evaluate the potential for the introduction and growth of microbes from external sources. This activity is intended to complement other work being conducted in Study 8.3.1.3.4.2 (Section 3.2.9 of this progress report).

No progress was made during the reporting period; this was an unfunded activity.

Activity 1.10.4.5.10 - Historical analogs. The objective of this activity is to identify sites of interest as historical analogs to Yucca Mountain (determined from the materials list developed in Activity 1.10.4.5.5); to collect samples from these sites; to analyze the samples for the information identified in Activity 1.10.4.5.5; to provide constraints for the experiments in Activities 1.10.4.5.7, 1.10.4.5.8, and 1.10.4.5.9; and to provide long-term data not obtainable from experiments for the development of the introduced material-rock-water interaction simulation activity (1.10.4.5.11).

No progress was made during the reporting period; this was an unfunded activity.

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Activity 1.10.4.5.11 - Computer modeling and code development. The objective of this activity is to develop the necessary codes (if not otherwise available) and to conduct predictions and simulations of experiments, natural analogs, and repository performance with respect to introduced materials effects on the near-field environment. Validation of developed models is included in this activity, which is complementary to Study 1.10.4.1 (Section 5.2.2 of this progress report).

No progress was made during the reporting period; this activity was not funded in FY 1996. Because of funding constraints, development was suspended of the data bases and models to predict and simulate the biotic and abiotic degradation of introduced materials as a function of time, temperature and water availability. The draft FY 1995 progress report (Meike and Spragge, 1995) discussed in Progress Report #14 (DOE, 1996b) has been completed

Forecast: Bounding predictions and sensitivity analyses will be developed for the chemical composition of water entering the repository and contacting waste packages. These analyses will incorporate the effects of man-made materials, using available data and models supplemented by limited new experimental work. Of the many materials that will be introduced into the repository setting, the most important is the cementitious class of materials. These materials are used for a number of different purposes and may be present in very large quantities. If they are not used, then large amounts of iron alloys will be necessary. Work will therefore emphasize cementitious materials.

Given the ubiquitous nature of microbes (including their presence in the ESF as introduced and native species), and their potential for significantly increasing corrosion rates and modifying chemistry (for which many examples exist in natural settings), process-level models presently available are not sufficient to demonstrate the quality of water in contact with the waste packages nor the corrosion rates of important materials in the presence of microbial activity. In addition, it is not clear under what conditions (excluding a very broad temperature range) microbial activity is significant and what the consequences are for the purpose of performance-level models. The necessary model development and supporting experiments will be initiated in the area of microbially mediated chemistry. Experiments will be conducted to support this work in which microbes isolated from the ESF (and in certain instances bred for diagnostic drug tolerances) will be tested for cessation of activity as a function of relative humidity, growth rate, starvation condition, temperature, radiation dose, and nutrient availability.

5.2.7 Related International Postemplacement Near-Field Environment Work

No progress occurred during the reporting period. As of November 8, 1995, the subsidiary agreements under which the cooperative work had been conducted were terminated and all international collaboration was discontinued.

The OCRWM had bilateral and technical cooperative agreements with Canada (Atomic Energy of Canada Limited [AECL]), Switzerland (Swiss National Cooperative for the Storage of Radioactive Waste [Nagra]), and Sweden (Swedish Nuclear Fuel and Waste Management

Company [SKB]) and has participated in activities of international organizations such as the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the Commission of European Communities (CEC).

Forecast: No international work is presently planned.

5.3 CHARACTERISTICS AND CONFIGURATIONS OF THE WASTE PACKAGES PRECLOSURE (SCP SECTION 8.3.4.3)

The purposes of this study are as follows:

1. To ensure that the waste package design complies with preclosure design criteria of 10 CFR 60.135 through analysis of the design and comparison of the design with the regulatory criteria
2. To obtain information on the physical characteristics of spent nuclear fuel and high-level waste that is to be accepted into the CRWMS. This information will include information on the suitability of a given waste form for emplacement, receipt rate projections, etc.

5.3.1 Information Need 2.6.1 - Design Information Needed to Comply with the Preclosure Criteria from 10 CFR 60.135(b)

The purpose of this activity is to obtain information necessary to ensure and verify that the waste package design complies with the specific design requirements of 10 CFR 60.135(b)(1) through (4). These requirements restrict the presence of explosive, pyrophoric, and chemically reactive materials in the waste packages. They also restrict the presence of free liquids in the waste package. Finally, they include requirements regarding the ability of the waste package to withstand handling loads and for waste package labeling.

Progress Report #13 (DOE, 1996j) discussed the compliance of light water reactor fuel and radioactive waste glass with the requirements of 10 CFR 60.135(b)(1) and (2). Chemical stability of several types of DOE-owned spent nuclear fuel is being investigated outside the Project. The fuel types include Fort St. Vrain fuel and three types of Shippingport fuel. The graphite blocks and graphite and silicon carbide coatings of the Fort St. Vrain fuel are not chemically reactive. Upon exposure to water, however, the uranium carbide and thorium carbide fuel particles will react to form uranium and thorium oxides plus hydrogen and hydrocarbon gases. The rate of production of these gases is expected to be low enough that the gases will dissipate harmlessly. The various Shippingport cores include both metallic and ceramic fuels. The metallic fuel is a uranium-zirconium alloy in the form of strips or plates. Because of the large zirconium content (93.67 percent) of the alloy fuel, it can probably be argued that this fuel is not chemically reactive. The ceramic fuels include $\text{UO}_2\text{-ZrO}_2$, $\text{UO}_2\text{-ZrO}_2\text{-CaO}$, and $\text{UO}_2\text{-ThO}_2$. Each of these fuels is clad

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with Zircaloy. These oxide fuels are even less chemically reactive than typical pressurized water reactor fuel.

The materials selected for disposal containers are listed in Section 5.1.4 of this progress report. These are standard engineering materials plus helium, an inert gas, as a fill gas. None of these materials is explosive, pyrophoric, or chemically reactive.

Analyses of waste containment during transportation and emplacement to address 10 CFR 60.135(b)(3) were reported in Progress Report #14 (DOE, 1996b). The analyses address the loads that result from handling accidents and rock falls. Additional work on rock fall is discussed in Section 5.1.3 of this progress report under Subactivity 1.10.2.3.2. Although degraded waste packages are emphasized in that subactivity, calculations for undegraded packages are included as limiting cases.

No work was scheduled this reporting period on methods to uniquely identify the waste packages to address 10 CFR 60.135(b)(4); that is an out-year activity. Because this requirement does not affect the viability assessment, no work is planned to address it before FY 1999.

Forecast: Work on the presence of explosive, pyrophoric, and chemically reactive materials and on free liquids is complete for light water reactor fuel, high-level waste glass, and disposal container materials. Additional analyses of DOE-owned spent fuel will be performed in FY 1997. Additional structural analyses for design basis rock falls have been delayed because rock fall data are still being acquired, so the rock fall size and frequency cannot be specified at this time. This work is planned to begin in FY 1997.

5.3.2 Information Need 2.6.2 - Design Information Needed to Comply with Preclosure Criteria from 10 CFR 60.135(c) for Waste Forms

The purpose of this activity is to obtain information necessary to ensure that high-level waste forms to be emplaced at the repository comply with the specific requirements of 10 CFR 60.135(c). This regulation requires that the waste forms be in solid form in sealed containers and that particulate waste forms be consolidated. It also limits the presence of combustible wastes.

Progress Report #13 (DOE, 1996j) discussed the compliance of light water reactor fuel and high-level waste glass with the requirements of 10 CFR 60.135(c). Studies of the chemical reactivity of certain types of DOE-owned spent fuel are discussed in Section 5.3.1 of this progress report.

Forecast: Work on this activity is complete with regard to light water reactor fuel and defense high-level waste glass.

5.3.3 Information Need 2.6.3 - Waste Suitability

The purpose of this activity is to develop the specifications for determining the suitability of spent nuclear fuel and high-level waste forms for emplacement at a repository.

On the basis of the work reported in Section 5.3.2 of this progress report, light water reactor fuel and defense high-level waste glass were determined to be generally suitable for disposal with regard to compliance with 10 CFR 135(c).

Information on the characteristics of the waste continues to become available as additional fuel is discharged and the system architecture is defined and refined. Historical and projected spent nuclear fuel discharges are updated annually by the DOE Energy Information Administration. These data are used by DOE in a variety of ways. Because these data contain not only discharge quantities but also spent nuclear fuel characteristics, the data bases form the foundation of any waste stream analysis.

System models are used to simulate the schedule and rate of pickup from utilities and to predict how the fuel will be containerized using container technology assumptions (capacity and heat limits) and the fuel characteristics. The system models also simulate movement of every container and spent nuclear fuel assembly through the CRWMS, resulting in a repository arrival profile. Since the last progress report, logistics arrival profiles consistent with the draft Revised Program approach system architecture and assumptions were produced in support of the Controlled Design Assumptions document (CRWMS M&O, 1996e). These data will continue to be provided to requesting DOE organizations as needed.

Forecast: The DOE is currently pursuing a strategy that will use private Regional Servicing Agents to provide waste acceptance and transportation of commercial spent nuclear fuel. Future work on waste acceptance will be contingent upon further definition of tasks to support the Regional Servicing Agents concept.

5.4 WASTE PACKAGE PRODUCTION TECHNOLOGIES (SCP SECTION 8.3.4.4)

5.4.1 Design Activity 4.3.1.1 - Waste Package Fabrication Process Development

The objective of this activity is to determine the processes to be used in fabricating the components of the waste packages other than the waste form itself. The fabrication techniques selected will be important in constructing a waste package that will meet repository containment and waste isolation performance objectives, because degradation mechanisms such as corrosion are often sensitive to fabrication techniques.

The Waste Package Fabrication Process Report (CRWMS M&O, 1996ee) was issued in August 1996. The report discusses container fabrication and the vendor requirements for fabrication. The cylinder-in-a-cylinder and the inner barrier clad designs are both workable methods of manufacture. Both designs are currently being used in industry for chemical and

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pressure vessels. The cylinder-within-a-cylinder design is the more economical of the two and will meet the requirements of the design if it can be shown that the outer barrier will galvanically protect the inner barrier. Two variations on this design are under consideration. The first is the slip-fit, in which the inner cylinder is "slipped" into the outer one. The other approach, the shrink-fit, involves heating the outer cylinder before joining it to the inner cylinder. As the outer cylinder subsequently cools and shrinks, contact between the two cylinders is enhanced. Benefits of a shrink-fit include secure positioning of the inner containment barrier, improved heat transfer from the inner barrier to the outer, and possibly improved electrical contact that would promote galvanic protection of the inner barrier. Potential fabricators contacted maintain that the cylinder-within-a-cylinder design will provide suitable electrical contact, but this has not been verified. If a mockup can be produced that allows for testing to answer the question of galvanic protection, this method will be the preferred fabrication method. If the mockup cannot be produced, the preferred method of fabrication will be to clad the inner barrier. The inner barrier clad method may be preferable from a performance standpoint but has the disadvantage of being significantly more expensive. The cost difference persists even if powder metallurgy is used for electrode production and extended stick-out is used to increase the deposition rate. Recommendation of this method would cause an increase of approximately \$90,000 per package over the prices given in the Total System Life Cycle Cost report (DOE, 1995n). The method has the advantage of producing two barriers that are actually bonded together. The inner barrier clad method is a proven method of manufacture that has been used in both Navy and commercial nuclear reactors.

Galvanic protection is expected to be very important to waste package performance, and current fabrication processes have not yet been demonstrated to provide this protection. Additional research on fabrication and bonding techniques may be needed if efforts to demonstrate this capability with current fabrication processes are unsuccessful. Newer methods such as explosive bonding and roll bonding may need to be investigated further. Currently, roll bonding is not feasible because of equipment limitations, but discussions with manufacturers suggest that this may be less of a problem in the future. It is also not known whether bonded plate of the required thicknesses can be formed into circular cylinders.

The informal estimates received from the fabricators show that earlier Management and Operating Contractor price estimates for a disposal container for canistered fuel are reasonably accurate. The agreement of these estimates lends credence to the other estimates.

Estimates for the ASTM B 424 N08825 (Alloy 825) and ASTM B 443 (Alloy 625) inner barriers show the ASTM B 443 material is more expensive than the ASTM B 424 N08825. Nevertheless ASTM B 443 has been chosen for the inner barrier. This decision is a result of the review of the corrosion data and the analysis of the two materials, as discussed in Section 5.1.4 of this progress report.

Forecast: The Waste Package Fabrication Process Report will be updated late in FY 1997. To support development of this report and evaluation of fabrication methods, full circular mockups will be fabricated. Fabrication work will address the manner of forming the thick-walled outer barrier cylinder, including any weld seam design that may be needed to complete this component.

These mockups will represent a number of options, which will be refined and narrowed as the design matures.

5.4.2 Design Activity 4.3.1.2 - Waste Package Closure Process Development

The objective of this activity is to determine, by using the logical sequence described for this issue, the process to be used in the final closure of the disposal containers. The closure process is very important to waste package performance. Inadequate closure or improper closure techniques could reduce the ability of affected waste packages to contain and isolate waste.

No progress was made during the reporting period; the work reported in Progress Report #14 (DOE, 1996b) marked the end of work in this area for the current phase of development.

Forecast: Under Revision 1 of the Civilian Radioactive Waste Management Program Plan (DOE, 1996a), this activity is expected to resume at the beginning of FY 1997 with the issuance of a technical guidelines document to construct a full circular mockup, 4 ft (1.3 m) long, to prove the shrink fit design for the outer and inner barriers and to prove the weld process developed in FY 1996.

5.4.3 Design Activity 4.3.1.3 - Waste Package Closure Inspection Process Development

The objective of this activity is to determine, by using the logical sequence described for this issue, the process to be used in inspecting the final closure of the disposal containers to ensure the closure is adequate, in compliance with design, and supportive of meeting repository overall performance objectives for waste containment and isolation.

Because of quality assurance questions, the Nondestructive Examination Technical Guidelines Document for closure welds (CRWMS M&O, 1995f) is being revised.

Forecast: The nondestructive examination program will be resumed during the next reporting period. This program includes developing a methodology to inspect the waste package closure weld process and an effort to develop a process to map the contact area between the cylinders in the shrink-fit mockup.

5.4.4 Design Activity 4.3.1.4 - Remote In-Service Inspection Development

The purpose of this activity is to develop an effective method and program for remote in-service inspection of the waste package. Remote inspection techniques will be needed to monitor waste package performance and condition during the preclosure period.

No progress was made during this reporting period; this was an out-year activity. Related work on performance confirmation concepts is discussed in Section 6.16 of this progress report.

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Forecast: No activity is forecast for in-service inspection program development because of its relatively low priority, given the length of time to beginning of emplacement.

5.4.5 Design Activity 4.3.1.5 - Internal Filler Material Process Development

The purpose of this activity is to determine a method of providing effective insertion of filler material into the waste package. Filler material may be used to absorb neutrons and/or to displace water from the waste packages. Fillers may thereby assist in criticality control.

The filler material development program demonstrated a high percentage fill of free space and the ability to measure bulk thermal conductivity of the candidate filler materials. Two different pressurized water reactor full-sized simulated fuel assemblies (15×15 and 17×17) and a simulated spent nuclear fuel basket cell made of polycarbonate were fabricated. Test objectives were fully met. In all tests, placement of steel shot with a nominal diameter of 1.0 mm resulted in filling over 94 percent of available free space around/within the simulated nuclear fuel assembly resting within the test fixture. This filling fraction easily exceeds the stated minimum acceptable value of 85 percent (MGDS Advanced Conceptual Design Report). That density would be sufficient to control criticality even if no other neutron absorbers are present, the fuel is fresh, and the waste package is suddenly flooded with water. The stated percentages of free space filling is the ratio of the bulk density for shot in the test fixture to the bulk density as measured under standard conditions. Additionally, selected physical properties of the steel shot filler material were measured, including bulk density, material density, bulk material angle of repose, and bulk material thermal conductivity over a temperature range of 50 to 350°C.

The filling and draining tests have demonstrated that placement of small-diameter steel shot may be readily accomplished. Even without vibration, the fill percentage within the fuel basket cells exceeded 96.5 percent for shot with a nominal diameter of 0.7 mm and exceeded 94 percent for shot with a nominal diameter of 1.0 mm. Either of these figures considerably exceeds the minimum required 85 percent figure. Although the minimum figure applies to the basket as a whole rather than just the cells for fuel assemblies, the 85 percent filling fraction should be easily attainable, given appropriate access to other free spaces in a waste package fuel basket. Similar results are expected for the other types of shot with high densities and smooth hard surfaces.

The procedure needed for adding filler material is the same as presented in Analysis of MPC Access Requirements for Addition of Filler Materials (CRWMS M&O, 1996ff). The procedure requires access to essentially all free spaces within a loaded canister. The design and operational requirements appropriate for small-diameter, nearly spherical shot include the following:

1. Design of the fuel basket and other internal structures shall not preclude attainment of a stipulated minimum percentage free volume fill, with the waste package oriented vertically, based on loose as-poured filler bulk density.

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2. The fuel basket and other internal structure shall be designed to provide access to essentially all free spaces; that includes free spaces within any flux trap basket designs. Accessibility to any space shall be as nearly as practical at the top of the free space, with the waste package oriented vertically.
3. Inherent in item 2 above is the requirement that the filler material "flow stream" would be directed over the entire open top-end cross-sectional area of the fuel basket and internal structure, whereupon the filler material is intended to flow down into all open free spaces. The filler material is intended to flow around and throughout each and every spent fuel assembly resting within the basket.
4. Achievement of the minimum fill would be by means of placement of a premeasured mass of filler material, the quantity appropriate to the particular type of spent nuclear fuel therein. This may be accomplished easily by using preweighed hoppers on a crane, or by a movable chute to cover the entire top of the waste package.

The tests were completed and the report issued in April 1996 (CRWMS M&O, 1996gg).

Forecast: No further activity is planned for this program. The Project believes it has adequately demonstrated a feasible process for insertion of filler material into the waste package, should use of filler be determined necessary or appropriate. Disposal containers for canistered fuel may require filler material, but no additional work on filler material is planned because of the Project emphasis on uncanistered fuel.

CHAPTER 6 - PERFORMANCE ASSESSMENT PROGRAM

INTRODUCTION

Performance assessment is the process of quantitatively evaluating component and system behavior, relative to containment and isolation of radioactive waste, to determine compliance with the numerical criteria associated with 10 CFR Part 60 and 10 CFR Part 960. Performance assessment includes evaluations (a) of the preclosure radiological safety of the public and workers and (b) of the postclosure waste isolation performance of the Mined Geologic Disposal System (MGDS). Performance assessment supports evaluations of site suitability, the design of the MGDS, and evaluations of regulatory compliance. A major aspect of performance assessment involves mathematical modeling of natural events, as well as processes and events induced by the construction and operation of the MGDS. The mathematical models are developed and validated and the computer codes that implement the mathematical models are verified, benchmarked, and documented. Laboratory and field measurements and experiments provide the understanding and data needed to develop and validate the mathematical models.

Current and Future Focus

A key element in performance assessment is total system performance assessment, which evaluates the postclosure performance of the combined natural and engineered barrier systems for expected and unexpected events and processes to demonstrate compliance of a potential MGDS at Yucca Mountain with the quantitative criteria of 10 CFR Part 60 and 10 CFR Part 960. Total system performance assessments are conducted iteratively to reflect the evolution of site data, the design of the engineered barrier system, and understanding of natural and engineered barrier system processes, conceptual and mathematical models, and computer codes. The latest assessment, Total System Performance Assessment - 1995 (CRWMS M&O, 1995a), was issued in the previous reporting period and summarized in Progress Report #14 (DOE, 1996b). Compared to earlier assessments, it included the effects of long-term periodic climatic changes, more representative conceptual models of the site hydrogeology, and more realistic models of engineered system behavior.

Current efforts are focused on preparing for the next total system performance assessment, planned for the 1997 to 1998 time frame, in support of the viability assessment. These preparations include sensitivity analyses to evaluate (a) the importance of the components and processes of the natural and engineered barrier system with respect to total system performance, (b) the effect of data and model uncertainties on the predicted component and total system performance, and (c) the validity of abstractions from detailed process models for total system performance modeling. These analyses require the updating of the modeling data bases with new site data, the evolving MGDS design, and the results of experimental research. These and other analyses will also support the testing of the hypotheses of the waste containment and isolation strategy. The results will be used to narrow and perhaps re-orient the scope of the site program and design work by identifying the additional information required for performance assessments in support of a license application after the viability assessment.

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During the reporting period, the major performance assessment emphasis was on (a) preliminary preclosure radiological performance analyses of the advanced conceptual design, (b) sensitivity analyses and conceptual model development in preparation of the planned total system performance assessment in support of the viability assessment, (c) ground-water travel time calculations for pre-waste-emplacement conditions and for post-waste-emplacement conditions that are affected by the heat of the emplaced waste, (d) waste form and waste container material experiments and related modeling to determine waste release rates and container degradation rates in various potential near-field repository environments, (e) evaluations of the potential impacts of site characterization activities, including the construction and operation of the Exploratory Studies Facility (ESF), on the postclosure performance of a potential repository, and (f) the completion of a performance confirmation concept study for identifying performance confirmation needs, emphasizing those that have to be considered in the ESF and MGDS design.

As noted in the Executive Summary, activities completed during this period indicated percolation flux at the repository level might be greater than previously thought. The data are preliminary and will require confirmation. Except where indicated otherwise, the analyses reported in this chapter did not use the higher percolation flux values because of the timing of the new results. However, the effects of the higher percolation flux are being evaluated in current analyses.

Following is a summary of the major performance assessment activities and results of the reporting period.

Preclosure Performance Assessment

Preclosure radiological safety analyses concentrated on identifying design basis events and consequence analysis in support of the classification analysis of items important to radiological safety. Also supported in this period was the planning and outline generation for Chapter 7, "Preclosure Radiological Safety" of the Project Integrated Safety Assessment in support of the viability assessment. Preliminary support was provided for the environmental impact statement effort. These activities considered the proposed rule change to 10 CFR Part 60 with regard to the definition of design basis events. Summaries follow.

The Preliminary MGDS Hazards Analysis report (CRWMS M&O, 1996u) was issued. It defines the set of hazards that could lead to a radionuclide release and the potential design basis events that apply to the potential repository at Yucca Mountain. For many potential initiating events, the effort used existing data to categorize the event (category one or two according to the U.S. Nuclear Regulatory Commission (NRC) proposed definitions, using probability as a discriminator).

Waste streams (spent nuclear fuel and high level defense waste) predicted to be received for disposal at the facility were analyzed for radionuclide content. The effective dose conversion factors were calculated for radionuclides in both waste categories for gaseous, volatile, and solid matter.

Two pilot analyses were completed that calculated radionuclide releases for the candidate design basis events from both the surface and subsurface operational areas of the potential repository and radiation exposures to both workers and members of the public.

Higher-Level Findings

A draft Notice of Proposed Rulemaking was prepared to amend 10 CFR Part 960 by adding a new site-specific subpart for Yucca Mountain. The proposed amendment would, in part, eliminate evaluation of the discrete technical guidelines under the system guidelines and the current system guidelines would be superseded by new preclosure and postclosure system guidelines. A determination of compliance with the new system guidelines would form part of the basis for evaluating the suitability of the Yucca Mountain site for development as a repository.

Total System Performance Assessment

The major total system performance assessment activities were (a) performance allocation analyses to test hypothesis of the U.S. Department of Energy's (DOE) waste containment and isolation strategy (DOE, 1996o) and provide guidance to site characterization activities and MGDS design, (b) sensitivity studies and abstractions of detailed process models to provide input for the total system performance assessment in support of the viability assessment, and (c) the preparation of a plan for the total system performance assessment to support the viability assessment. Summaries follow.

Using a performance allocation approach, sensitivity analyses were conducted to evaluate the relative and absolute performance of the total system and how this performance varies along the radionuclide transport path from the potential repository to the biosphere (CRWMS M&O, 1996hh). The total mass of radionuclides and radiation doses were used as performance measures because of uncertainties in future regulatory standards. The analyses were then used to illustrate the importance of several key hypotheses of the waste containment and isolation strategy (DOE, 1996o). The results were used to establish priorities for developing and testing process models. Those priorities were then used to prioritize site and design activities to be conducted in fiscal year (FY) 1997 in support of the viability assessment.

Several model abstractions were evaluated for the following key processes (CRWMS M&O, 1996hh): (a) the unsaturated zone percolation (including the net infiltration), (b) the thermal hydrology at the scale of a drift, (c) the degradation of waste packages, (d) the dissolution rate of the waste form (including the potential effects of cladding), (e) the role of dilution in the saturated zone, and (f) the unsaturated zone radionuclide transport system. These process-level model abstractions and sensitivity analyses evaluated the relative importance of input parameters, including their uncertainties, with respect to the computed output. On that basis, response functions were derived in terms of tables, curves, and surfaces that will become input to total system performance assessments.

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A performance assessment working data set for detailed process modeling and total system performance assessments was updated. The data set includes data from site characterization and recent hydrologic laboratory experiments.

A report identifying a representative set of features, events, and processes for constructing scenarios to be modeled to determine the effects of seismic activity on a potential repository at Yucca Mountain was issued (Barr et al., 1996).

A Total System Performance Assessment - Viability Assessment Plan (CRWMS M&O, 1996ii) was prepared that describes the technical work, organizational responsibilities, and schedules for the process and overall system modeling required for the viability assessment.

Ground-Water Flow Experiments and Modeling

Ground-water travel time analyses were performed for both pre-waste and post-waste emplacement conditions to evaluate various conceptual and mathematical models for ground-water flow and the coupling of unsaturated and saturated zone flow. These activities evaluated the relative importance of scaling, heterogeneities, and alternate conceptual models in hydrologic modeling. In addition, the effects of heat on the hydrologic flow field were explored, focusing on the numerical formulations needed to link macroscopic models provided by the Site Program into the smaller-scale models that investigate the near-field environment. Reporting of previously terminated experimental work continued. Summaries are provided below.

A report on the FY-1995 pre-waste-emplacement ground-water travel time analysis was issued (Altman et al., 1996a) that includes the definition of the conceptual model, the selection of hydrologic parameters, and the simulation of rock properties and ground-water flow for pre-waste-emplacement ground-water travel time analyses.

To evaluate differences in model scales, simulations were performed at the laboratory, drift, and mountain scale (Altman et al., 1996b). Averaging techniques and a bulk upscaling method were successful in approximately reproducing the results of a laboratory imbibition experiment on a slab of tuff from the Topopah Spring hydrogeologic unit (TSw). Geometric averaging was the best of the different averaging techniques, implying that the heterogeneous domain for this TSw slab is spatially uncorrelated.

The same modeling studies show that (a) the spatial heterogeneity of flow and transport processes is important (including the location and spatial density of high permeability features or fracture networks), (b) transient infiltration pulses need to be included in the calculations, (c) fracture-matrix interactions are clearly critical to flow through the mountain and must be incorporated into the mathematical models, (d) for low surface water infiltration rates, thin layers within the tuff of the Paintbrush nonwelded hydrogeologic unit (PTn) could divert much of the vertical percolation laterally and thus influence the flux at the potential repository horizon, and (e) for the higher surface water infiltration rates, most of the vertical percolation would continue downward to the potential repository horizon.

The first set of fully three-dimensional, mountain-scale, coupled heat and fluid flow calculations of the unsaturated zone were conducted (Francis et al., 1996). Two alternative conceptual models of fluid flow in fractured porous media, an equivalent-continuum model and a generalized-equivalent continuum model were used with both homogeneous and heterogeneous rock properties. For base-case assumptions regarding infiltration (average of about 0.3 mm/yr) and thermal loading (83 kW/acre), the thermal-hydrological response of the system is dominated by buoyant gas phase convection above most of the potential repository during the first 1000 years following waste emplacement. Heat transfer is enhanced above the potential repository in a zone of countercurrent two-phase flow relative to the region below the potential repository. A zone of increased liquid saturation from the accumulation of condensate forms above a dryout zone, which persists for approximately 1000 years near the center of the potential repository, but may not form near the potential repository edges. Liquid flux through the potential repository may increase by a factor of up to several hundred relative to ambient conditions during the heating and cooling, depending on location. The extent, duration, and magnitude of the temperature and liquid saturation perturbations were calculated to be somewhat larger for a thermal load of 100 kW/acre than for the base case, but the qualitative behavior of the system is similar for both cases. Heterogeneous material properties in the TSw resulted in slightly higher simulated peak temperatures at the potential repository horizon and a non-uniform distribution of condensate above it relative to the homogeneous case.

Other simulations, of both the unsaturated zone and saturated zone, evaluated two equivalent-continuum models and a dual-permeability model with different boundary conditions at the water table for a thermal load of 83 kW/acre (Ho et al., 1996). For the unsaturated zone, the results show the generation and subsequent movement of large amounts of condensate above the potential repository for an infiltration of 0.3 mm/year. The equivalent-continuum model predicts rewetting of the potential repository region within several thousand years as a result of the downward movement of the accumulated condensate through the matrix during cooling. The dual-permeability model predicts that a significant amount of the condensate drains through the fractures during the heating phase (<1000 years), lowering the overall water content in the system. Fluxes in the fractures caused by condensate drainage can be 100 times greater than ambient percolation in the dual-permeability model, leading to the possibility of focused flow to the potential repository. However, all the simulations show that the generated heat is sufficient to dry the potential repository, which prevents any through-flowing liquid for a period between about 100 years and several thousand years. An infiltration of 10 mm/year, however, is sufficient to eliminate the development of a dryout zone at 83 kW/acre.

Saturated zone model results indicate that the temperature increases significantly at the water table beneath the potential repository, implying that a heat exchange boundary condition at the water table is more appropriate in unsaturated zone modeling than the commonly assumed constant-temperature boundary. The simulated thermal plume in the saturated zone has temperatures at the water table as high as 70°C, extends up to 5 km downgradient of the potential repository, persists well beyond 10,000 years, and increases saturated zone ground-water velocities by as much as a factor of two below the potential repository. These results suggest the possibility of geochemical and mineralogic alterations to the saturated zone from waste heat.

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Three reports were completed (Glass et al., 1996; Tidwell, 1996; Glass et al., in prep.) that document experimental work in support of ground-water flow and solute transport model validation terminated in FY 1995. Data reduction and image analysis continued for two fracture-matrix interaction data sets collected in FY 1994 and 1995. In these tests, x-ray absorption imaging was used to measure the imbibition of water from a slot fracture into thin slabs of volcanic tuff.

A scientific notebook is being prepared to document results of infiltration studies conducted in the zone excavated around the Fran Ridge Heater-Block Test. The notebook will include three-dimensional fracture maps, infiltration flow paths marked by dyed water, and characteristics of the applied boundary conditions. Modeling of a high-infiltration test at Fran Ridge with the thermal-hydrological computer code TOUGH2 showed that the code's dual-permeability model agreed with the experimental measurements, while the code's equivalent-continuum model calculated only minimal fracture penetration in contrast to the actual penetration (Eaton et al., 1996). The results indicate that for high infiltration rates the dual-permeability model should be preferred over the equivalent-continuum model.

Three-dimensional drift scale isothermal ground-water flow modeling with heterogeneous hydraulic conductivities indicates that the spatial distribution of seepage into the drifts varies by three orders of magnitude and that large infiltration pulses (280 mm/yr up to 28 000 mm/yr) bypass the rock matrix and result in water dripping into the drifts. The hydraulic conductivity was a distribution with two peaks, matrix and fracture. The mean hydraulic conductivity for the matrix was 10^{-18} m^2 with half an order of magnitude standard deviation and for the fractures was 10^{-12} m^2 with a third of an order of magnitude standard deviation. The analyses were conducted at the drift scale and percolation pulse of 28, 280, 2800, and 28 000 mm/yr were applied both uniformly and at a single point 10 m above the drift until dripping was observed in the drift. Dripping was observed for all simulations with 280 mm/yr and higher, generally after a few simulated days.

Two-dimensional mountain-scale modeling of coupled unsaturated and saturated nonisothermal multiphase flow for a thermal loading of 83 kW/acre predicts a maximum temperature rise at the water table of 30°C and liquid and gas flow several orders of magnitude above ambient conditions at the potential repository horizon. For 0.1 mm/yr ambient water percolation, the potential repository horizon dries out after 100 to 500 years and remains dry for about 2000 years. For 4.4 mm/yr ambient water percolation, the potential repository horizon does not dry out because the percolation is higher than the available energy for vaporization.

Performance Confirmation

A performance confirmation concept study report was issued (CRWMS M&O, 1996jj). The report identifies the processes to be simulated for postclosure performance assessment in support of a license application, lists the site and MGDS design parameters needed for these analyses, develops criteria for selecting performance confirmation parameters from this list, and on that basis, recommends the parameters that need to be measured, monitored, observed, tested, and analyzed following the submittal of a license application to construct a repository at Yucca

Mountain. Finally, performance confirmation concepts are recommended that describe specific methods for the performance confirmation data acquisition. These concepts then provide the basis for specific requirements that are recommended for consideration in the MGDS design to accommodate the data acquisition.

Engineered Barrier Materials Experiments and Modeling

Engineered barrier materials experiments and modeling included testing and performance evaluations of spent nuclear fuel and candidate waste container materials, backfill evaluations, modeling of waste container performance, and reporting of previously conducted work. Summaries follow. Refer to Chapter 5 for related work.

Volume 3 of the Engineered Materials Characterization Report was revised (McCright, in prep.) to include the results of testing and modeling activities that have occurred since the original issue of the report (Van Konynenburg and McCright, 1995). Volume 1 (on the background and history of the engineered barrier system candidate materials) and Volume 2 (on the physical and mechanical properties of the candidate materials) were not revised this report period. A degradation mode survey on the effects of fabrication and welding on the performance of candidate corrosion-resistant nickel-base and titanium-base alloys, discussed in Progress Report #14 (DOE, 1996b), will be published shortly (Goldberg and Dalder, in prep.).

Disposal container materials were selected for the viability assessment. The selection covered disposal containers for canistered and uncanistered fuel as well as for defense high-level waste glass. All major components, including corrosion-allowance and corrosion-resistant barriers; basket plates, tubes, and guides; fill gas; and canister guides were considered. Because of the broad coverage of components, the work also required development of selection criteria and weighting factors for many components.

Alloy 625 (ASTM B 443), a nickel-chromium-molybdenum alloy, was added to the corrosion testing program. Alloy 625 was one of the materials used in evaluating the weld-clad process (see below) for fabricating a double-walled container. Alloy 625 has been used in many corrosion applications, both in aqueous media and in higher temperature, often polluted, atmospheres. Alloy 625 is often used for making filler welds in other high-nickel alloys and is considered one of the most weldable alloys in this class of materials. The alloy contains an intermediate level of molybdenum (8 to 10 percent) compared with the other candidate materials, Alloys 825 and G-3 (3 to 6 percent) and Alloys C-22 and C-4 (14 to 16 percent), and consequently its localized corrosion resistance in very aggressive environments would also be expected to be intermediate.

Alternative fabrication processes to achieve galvanic protection of the inner waste package barrier by the outer barrier were identified. A key issue is the contact to be achieved between the dissimilar metals. Fabrication options include (a) a slip-fit process by slipping two separately fabricated containers inside one another, producing only a casual contact; (b) a shrink-fit process with this option to increase the contact; and (c) a weld-clad process in which the inner barrier

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material would be deposited from welding electrode material in multiple passes for a metallurgical bond.

Related to above, a degradation survey on the galvanic corrosion behavior of candidate corrosion-allowance materials and candidate corrosion-resistant materials identified combinations of materials that could enhance, rather than retard, corrosion (Roy et al., 1996). Specimens for galvanic corrosion tests using electrochemical methods were acquired but testing has not yet started.

Chemical additives to the backfill were evaluated, including lime (CaO) to control the pH to a more alkaline value and thereby reduce corrosion of the container material, and either iron (Fe) as a powder or magnetite (Fe₃O₄) to control the Eh of the near-field environment (CRWMS M&O, 1996s). While control of the reduction-oxidation condition in the environment may mitigate some corrosion effects, the principal reason for adding reducing agents is to control the oxidation state of radionuclides, especially neptunium, to render them less mobile and therefore less likely to be released from the engineered barrier system. Additionally, the lime addition would react with carbon dioxide (CO₂), including any escaping ¹⁴CO₂ from the waste package, to form insoluble calcium carbonate (CaCO₃). Quartz sand was considered as the primary backfill material because it has no internal porosity (compared with crushed Topopah Spring tuff) and therefore does not wick water to the waste package. The study concluded that these additives, even if added in generous proportions, are not effective in modifying the environment in the time periods when they would be needed.

Preparation for long-term corrosion tests (at least five years) continued with the installation of test vessels and associated components (McCright, in prep.). The dimensions and weights of several thousand test specimens were determined. Technical procedures for the testing and for software control were written. Testing started just before the end of the reporting period.

Thermogravimetric analysis studies continued to evaluate aqueous film corrosion processes (McCright, in prep.). Tests were performed on carbon steel (AISI 1020) specimens with different surface conditions under 60 to 90°C temperatures and a wide range of humidities. Initial corrosion rates are much higher for specimens that were etched chemically or coated with salt (NaCl) than for polished specimens.

Testing of carbon steel specimen in microbe-inoculated test cells began as part of the studies of microbiologically influenced corrosion (McCright, in prep.). Corrosion rates, measured for 65 days by the end of the reporting period, for different microbes and different combinations of microbes varied by several factors and were up to five times higher than for the abiotic control tests.

Electrochemical cyclic potentiodynamic polarization experiments of the nickel-base and titanium-base corrosion resistant alloys continued to evaluate localized corrosion, such as pitting and crevice corrosion (McCright, in prep.). In general, of all the materials tested, Alloys C-4 and C-22, and Ti Gr-12 exhibited the maximum corrosion resistance, showing no pitting or general

corrosion in any environments tested. These three highly corrosion-resistant materials maintained their shiny surface appearances even after exposure to the test solutions.

Development of the phenomenological stochastic pitting corrosion model PIGS continued, focusing on corrosion-resistant materials (e.g., one of the nickel-base or titanium-base alloys) and a limited effort on the degradation of corrosion allowance materials (e.g., carbon steel) by dry oxidation or general atmospheric corrosion (Henshall, in prep.; McCright, in prep.). The model simulates the stochastic initiation, time evolution, and pit growth cessation of the distribution in pit depths as a function of the near-field environment.

Work started on a deterministic model to predict long-term effects of low-temperature oxidation, initially focusing on carbon steel, the principal candidate for the outer waste package barrier (McCright, in prep.). Tentative model results, which are based on experimental evidence, indicate that dry oxidation is not expected to significantly degrade the performance of thick corrosion-allowance materials for hundreds to thousands of years.

The pitting corrosion submodel in the waste package radionuclide release computer code YMIM (Gansemer and Lamont, 1995) was expanded to consider the possibility of cessation of pit advance as a pit becomes larger. Model testing indicates that it may be possible to design waste package containers such that only a small fraction would be completely penetrated over the expected regulatory period of the repository.

Analyses were performed with YMIM to evaluate the changes in pH of the water potentially contacting waste packages that result from the corrosion of the metal waste package containers and leaching of concrete in the emplacement drifts. While the concrete may increase the initial pH of 7 to 12, the iron would reduce it to 6 initially and to 10 in later years. This reduction may last from about one hundred to many thousands of years, depending on the range of iron solubility in commercially produced steel. The spent nuclear fuel dissolution rate at a pH of 10 is about one third of that at a pH of 6.

The stochastic waste package degradation computer code WAPDEG was developed (Atkins and Lee, 1996; Lee et al., 1996a). The current version computes the failure time of waste packages (defined as having at least one pit penetration) and the subsequent pitting degradation of the waste packages. Compared to the approaches used in past total system performance assessments, the model includes improvements in the corrosion models, additional important corrosion modes, and more realism in modeling the corrosion expected in the drift environments of the potential repository.

Waste Form Experiments and Modeling

Waste form experiments and modeling included testing and nuclear performance evaluations of spent nuclear fuel and defense waste glass dissolution and leaching, spent nuclear fuel oxidation, thermodynamic data development for geochemical modeling, and modeling of waste form dissolution. Summaries follow.

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The Waste Form Characteristics Report was revised (Stout et al., 1996) to include the results of testing and modeling activities that have occurred since the original issue of the report (Stout and Leider, 1994).

Flow-through tests of spent nuclear fuel focused in four different areas: (1) UO_2 matrix dissolution rate tests on pressurized and boiling water reactor fuels at a variety of burnups, (2) dissolution rate tests with oxidized fuels, (3) grain-boundary penetration rate tests, and (4) gap inventory tests for iodine-129. Cesium and strontium dissolved congruently with uranium, which is consistent with data obtained with grain specimens of the types of fuel that have been tested so far. However, the technetium-99 data have not been consistent for the different spent nuclear fuel specimens. Differences in spent nuclear fuel dissolution for different burnup rates ranged from almost none to factors of seven depending on experimental conditions.

Unsaturated drip tests of spent nuclear fuel were performed with two commercial spent nuclear fuels at three different drip rates. The observed sample reaction trends have closely replicated those that occur in natural geologic systems, such as the Nopal I deposit in Mexico, and can consequently be used to simulate the uranium reaction progress expected in a potential repository at Yucca Mountain.

Dry-bath weight gain tests continued and thermogravimetric apparatus tests began to determine spent nuclear fuel oxidation at a range of temperatures. Results to date are inconsistent, which may be caused by chemical variations of the fuel pellet surface compositions.

Long-term leach testing of defense waste glass compositions is continuing to provide glass alteration and radionuclide release rate data. No new sample analyses were performed.

The hardware facilities and relational data base system for the GEMBOCHS thermodynamic data base and software library were upgraded to improve data base security and run time. GEMBOCHS was augmented by including reference-state dissociation constants for approximately 300 rare-earth aqueous complexes and 150 solids (Spahiu and Bruno, 1995). New thermodynamic data file suites were generated for use with both the geochemical simulation code EQ3/6 (Daveler and Wolery, 1992; Wolery, 1992a and b; Wolery and Daveler, 1992) and the software package GWB (Bethke, 1994) and are available to Yucca Mountain Site Characterization Project (Project) participants from the Internet.

Experimental data on spent nuclear fuel oxidation, dissolution, and leaching are being used to develop a mechanistic mathematical model for these processes, and thus radionuclide release from the spent nuclear fuel (Stout, 1996). Similarly, a mathematical model of defense high-level waste glass degradation is being developed, which considers chemical effects of the near-field environment, principally of cations like magnesium, iron, and aluminum.

Site Impact Evaluations

Site impact evaluations are performed to estimate the potential effects of site characterization activities, including the construction and operation of the ESF, on testing and the

waste isolation capability of the Yucca Mountain site. Controls on activities are established, if needed, based on these technical analyses to limit adverse effects. Evaluations during this reporting period include (a) a revised analysis of water use in the ESF, (b) the discharge and loss of organic materials at the site surface, and (c) the use of concrete in the ESF. The previously established limits for underground water use (CRWMS M&O, 1995g) are being revised in light of a new compilation of hydrogeologic properties for Yucca Mountain (CRWMS M&O, 1996f) and updated process models. An analysis of the use of organic materials that may be lost to the geologic environment at the site surface is consolidating the many specific evaluations for surface-based testing activities into a single, comprehensive evaluation. Work concerning the use in the subsurface ESF and potential repository of committed concrete (i.e., concrete that will remain underground in a potential postclosure repository) is attempting to bound the geochemical effects of such materials on the potential repository performance.

Changes from Previous Progress Reports

This progress report continues the format of Progress Reports #13 (DOE, 1996j) and #14 (DOE, 1996b) for Chapter 6, which established a one-to-one correspondence with the Site Characterization Plan (SCP) (DOE, 1988) fourth-level performance assessment sections. Section 6.21 "Site Impact Evaluations" does not have a corresponding SCP section. As before, not all the SCP sections, however, apply any more to present Project activities. In addition, some performance assessment activities are more logically related to technical subjects covered in other progress report chapters. These instances are called out in the affected sections of this chapter. Appendix A summarizes the SCP approach for performance assessments, describes changes in these plans, explains the reasons for these changes, and lists references where these changes and reasons are documented.

6.1 STRATEGY FOR PRECLOSURE PERFORMANCE ASSESSMENT (SCP SECTION 8.3.5.1)

SCP Section 8.3.5.1 addresses the development of the preclosure performance assessment strategy for resolving Key Issue 2. This issue asks whether the projected releases of radioactive materials to restricted and unrestricted areas and the resulting radiation exposures of the general public and workers during repository operation, closure, and decommissioning at Yucca Mountain meet the applicable requirements set forth in 10 CFR Part 20, 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191. In determining the strategy for preclosure performance assessment, due consideration has been given to possible changes in these regulations.

The objective of the preclosure risk assessment methodology program is to develop a consistent preclosure safety assessment methodology. The SCP identified ten categories of risk that may be considered, of these five involve radiological risk, and only those are addressed in Chapter 6.

Where possible the methodologies to predict the consequences of radionuclide releases have been taken from previously successful license applications and environmental impact

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statements. To date, the analysis have been limited to the primary pathway of inhalation only. This route is being pursued because of the close parallels between the waste handling operations required at the potential repository and those required at reactor facilities and temporary storage sites for spent nuclear fuel.

Effort this period was primarily focused on the definition and analysis of the design basis events in support of the classification analysis of items important to radiological safety. Under direction of the Determination of Importance Group, a multidiscipline team defined a comprehensive set of events from which the bounding set of design basis events will be selected. For this work, the team assumed that the NRC's proposed rule change for 10 CFR Part 60 concerning design basis events will be adopted. This change, if and when implemented, will categorize all design basis events into two groups. Category one design basis events will embrace all events that are likely to occur during operations at the facility and thus include normal operations. Events considered credible but unlikely to occur during the operational phase of the facility are considered to be category two design basis events. Events considered included external events (initiating events outside the control of the design team) and internal events such as equipment failure and human error. The external events carried forward for further consideration included seismic activity (earthquake and fault displacement), aircraft crash, extreme winds, ash falls from volcanic activity, tornados, and lightning.

The comprehensive set of events defined in the Preliminary MGDS Hazards Analysis report (CRWMS M&O, 1996u) were screened for credibility of occurring at the potential repository site and for their capability to result in a radionuclide release from containment barrier(s) (see Section 4.2.1 of this progress report for the complete list of external events both included and excluded). The resulting screened events are those that are candidates for becoming design basis events. Before the definition of the design basis event list, a limited but representative set of events, including a nonmechanistic failure of a waste package, was selected for consequence analysis under a pilot (i.e., scoping) evaluation scheme. The examples used for scoping purposes were drawn from operations primarily in the surface facilities, where the waste form can be in one of its more vulnerable states. The nonmechanistic waste package failure was taken as the underground facility event because in this part of the repository the waste is always inside the robust waste package.

These pilot calculations analyzed the radiation dose consequences as a function of distance from the release point. Progress on this work is reported in Sections 6.3, 6.4, and 6.5 of this progress report. Additional details concerning the classification effort are also reported in Section 4.2 of this progress report.

Some effort was devoted to identifying the details required to support the findings of the viability assessment. In particular, the outline of Chapter 7, "Preclosure Radiological Safety," of the Project Integrated Safety Assessment was issued in draft form. The final version of the outline was incorporated in the "Management Plan for the Development of a Project Integrated Safety Assessment" (CRWMS M&O, 1996kk).

Forecast: If and when necessary, more refined and detailed models will be used for consequence analyses. The more global requirements imposed by the environmental impact statement are more likely than the NRC licensing requirements to drive this activity. In FY 1997, a bounding set of design basis events will be defined and their associated radiation dose consequences analyzed. The next level of detail and individual tasks for the effort to produce the Project Integrated Safety Assessment Chapter 7 will be defined.

6.2 WASTE RETRIEVABILITY (SCP SECTION 8.3.5.2)

SCP Section 8.3.5.2 addresses Issue 2.4, which asks whether the repository can be designed, constructed, operated, closed, and decommissioned so that the option of waste retrieval will be preserved as required by 10 CFR 60.111.

No work was conducted that focused on the retrievability requirements and/or design options for retrieval during this reporting period.

Forecast: A retrievability study is planned for FY 1997. The objective of the study will be to develop the technical rationale for a decision regarding the design approach to be used for complying with the 10 CFR Part 60 requirements related to retrievability. Options available for potentially satisfying these requirements range from one extreme of developing a design that allows retrieval, if necessary, but does not include features that facilitate the retrieval, to the opposite extreme of including features in the design that facilitate retrieval and, indeed, build the retrieval capability into the repository at the time of repository development. This activity will make recommendations regarding the extent to which the repository and waste package designs should accommodate the retrieval option, develop requirements associated with the time required for retrieval, and identify the potential conditions requiring retrieval. This study will also develop and evaluate potential scenarios concerning the final disposition of the retrieved waste.

This study is required to provide the technical bases for retrievability requirements and to provide sufficiently specific requirements for design development, using 10 CFR Part 60 as the basis for developing the requirements. Retrieval must be addressed at the level of detail needed to support development of the license application plan (FY 1997) and the license application itself. The results of this study will be used by the surface and subsurface design organizations to facilitate the FY 1997 retrieval design development. The regulatory and licensing organization will use the results in developing the license application plan for FY 1997.

6.3 PUBLIC RADIOLOGICAL EXPOSURES - NORMAL CONDITIONS (SCP SECTION 8.3.5.3)

SCP Section 8.3.5.3 addresses Issue 2.1, which asks whether expected preclosure radiation doses received by members of the public during repository operation, closure, and decommissioning will be less than allowed by 10 CFR 60.111, 40 CFR 191 Subpart A, and 10 CFR Part 20.

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The proposed rule change to 10 CFR Part 60 defines two categories of design basis events. Category one events are those that are reasonably expected to occur during the life of the facility. Thus all activities that will be performed as normal operations will be classed as category one design basis events. Although some effort was devoted to defining the nonroutine design basis events (i.e., those events expected to occur but are not scheduled to occur), no effort has been expended in evaluating radiation exposures from these events. Radiation dose consequence calculations were performed for the pilot examples for the category one design basis events expected to occur during normal operations.

A small effort was devoted to reviewing the requirements for the environmental impact statement.

6.3.1 Performance Assessment Activity 2.1.1.1 - Refinement of Site Data Parameters Required for Issue 2.1

The objective of this activity is to refine the population, agricultural, surface water, meteorological, host rock, and offsite nuclear installation data needed for determining preclosure radiological exposures to members of the public resulting from normal repository operations. This information is collected as part of the environmental, geological, and hydrological site programs and is reported in Chapter 3.

This effort was conducted simultaneously with the pathway analysis and data requirements for the postclosure period. For the effects of radionuclide intake by inhalation, the NRC guidance provided in Regulatory Guide 1.25 (NRC, 1982) was used to determine atmospheric dispersion of released radionuclides. For the initial assessment supporting the viability assessment/Project Integrated Safety Assessment evaluation, no dispersion credit will be taken for the height of the exhaust stack because of the difficulties of modeling the airflow and turbulence near the potential site.

The biosphere radiological assessment model that is being developed to support the postclosure radiation dose estimation will have the capability to evaluate long-term bioaccumulation impacts of the preclosure radioactive releases. At this time, no computations have been completed but the model has been developed to the point where preclosure radiation dose estimation will be possible.

Forecast: The existing atmospheric data will be reviewed and used to predict site-specific dispersion factors. A sensitivity study will be initiated to identify the important parameters. The necessary data reduction and analysis of the existing site-specific data will be performed to generate actual atmospheric dispersion values.

6.3.2 Performance Assessment Activity 2.1.1.3 - Advanced Conceptual Design Assessment of the Public Radiological Safety during the Normal Operations of the Potential Yucca Mountain Repository

The objective of this activity is to perform a public radiological safety assessment of the advanced conceptual design of a potential Yucca Mountain repository. Secondary objectives are to provide information for the refinement of the site data parameters list for SCP Issue 2.1 (Performance Assessment Activity 2.1.1.1, see Section 6.3.1 of this progress report) and to provide feedback to the preclosure risk assessment methodology program for future methods development activities (Performance Assessment Activity 2.1.1.2, see Section 6.3.3 of this progress report).

The safety assessments are being performed by a multidisciplined group drawn from the surface and subsurface facilities and waste package design groups in addition to performance assessment and the environmental group. The work is under the direction of the Determination of Importance group in Systems Engineering. The primary objective of the effort is to support the DOE in the updating of their Q-List of Items Important to Radiological Safety. The work to support this objective has to be performed under QA procedures. This necessitates referencing design documents that are not subject to evolution over time. The latest of these appropriate designs in the Advanced Conceptual Design Report.

Using the technical expertise from all the design groups to evaluate the "radiological safety" of the proposed facility, automatically ties in safety considerations to the engineering evolution of the viability assessment design. Once the viability assessment design is "frozen" it will be evaluated for radiological safety under QA procedures. However, the closely coupled technical feedback from the Advanced Conceptual Design Report evaluation to the viability assessment design will ensure that there are no surprises hidden in the final viability assessment design. The approach being adopted by the Program keeps costs in control by limiting the number of formal evaluations under QA procedures during transition from one design phase to the next, while providing design feedback.

As discussed earlier in Section 6.3 of this progress report, "normal operations" will probably have to consider those events that are likely to occur only once during the life of the facility. To this end, the Preliminary MGDS Hazards Analysis was issued (CRWMS M&O, 1996u). This report provides a comprehensive list of possible events, both internal and external initiating events, that were then screened for relevancy to radioactive releases at the potential repository. Bounding radionuclide release terms were developed for the waste forms and documented in Source Terms for Design Basis Event Analyses (CRWMS M&O, 1996v). Pilot analyses are in progress for both the surface and subsurface portions of the potential repository to evaluate whether the radiological consequences from the events selected (e.g., fuel assembly drop, waste canister drop, mechanistic release from a waste package) are within regulatory limits for the public (CRWMS M&O, in prep[a] and [b]).

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Forecast: More design basis events applicable to the advanced conceptual design of the repository (including normal operations from the previous definition of such) will be analyzed. Radiological dose consequences will be calculated for the environmental impact statement.

6.3.3 Performance Assessment Activity 2.1.1.2 - Development of Performance Assessment Activities through the Preclosure Risk Assessment Methodology Program

The objective of this activity is to benefit from the performance assessment methods development efforts for the preclosure risk assessment methodology program. A secondary objective is to use the information developed in this activity to assist in refining the site parameters list for SCP Issue 2.1 (Performance Assessment Activity 2.1.1.1, see Section 6.3.1).

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997.

6.4 WORKER RADIOLOGICAL SAFETY - NORMAL CONDITIONS (SCP SECTION 8.3.5.4)

SCP Section 8.3.5.4 addresses Issue 2.2, which asks whether the repository can be designed, constructed, operated, closed, and decommissioned in a manner that ensures the preclosure radiological safety of workers under normal operations as required by 10 CFR 60.111 and 10 CFR Part 20.

Because the rule change proposed to 10 CFR Part 60 by the NRC will consider normal operations to be category one design basis events and limit exposure to workers as given in 10 CFR Part 20, the distinction between a normal event and likely but off-normal event vanishes. As a result, design basis events (now including normal operations) are being defined that apply to both workers and members of the public. These analyses are being undertaken simultaneously. At present, the analyses have focused on anticipated but unplanned events (as opposed to scheduled activities during facility operation). These investigations, because of the commonality of cause, are being conducted in parallel with the work reported in Section 6.3.

Forecast: The advanced conceptual design data for the repository will continue to be used to estimate doses to workers from routine radioactive releases.

6.4.1 Performance Assessment Activities 2.2.1.1 and 2.2.2.1 - Refinement of Site Data Parameters Required for Issue 2.2

The objective of this activity is to refine (a) the data needed on the subsurface radiation environment due to natural and man-made radioactivity and (b) the meteorological, host rock, and ground-water data needed for determining radiological exposures to workers resulting from

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normal repository operations. This information is collected as part of the environmental, geological, and hydrological site programs.

Forecast: Specific site data requirements, if any, that are required for predicting worker radiological exposure will be identified.

6.4.2 Performance Assessment Activities 2.2.1.2 and 2.2.2.3 - Advanced Conceptual Design Assessment of the Worker Radiological Safety during the Normal Operations of the Potential Yucca Mountain Repository

The objective of this activity is to perform a worker radiological safety assessment of the advanced conceptual design for a potential Yucca Mountain repository. See also Section 6.3.2 for a brief discussion of the Advanced Conceptual Design Report and viability assessment design. Secondary objectives are to provide information for the refinement of the site data parameters list for SCP Issue 2.2 (Performance Assessment Activities 2.2.1.1 and 2.2.2.1, see Section 6.4.1 of this progress report) and to provide feedback to the preclosure risk assessment methodology program for future methods development activities (Performance Assessment Activity 2.2.2.2, see Section 6.4.3 of this progress report).

Radiation doses from category one design basis events have been evaluated in parallel to the calculation of doses to members of the public (see Section 6.3.2 of this progress report).

Forecast: More design basis events applicable to the advanced conceptual design of the repository (including normal operations from the previous definition of such) will be analyzed. Radiological dose consequences will be calculated for the environmental impact statement.

6.4.3 Performance Assessment Activity 2.2.2.2 - Development of Performance Assessment Activities through the Preclosure Risk Assessment Methodology Program

The objective of this activity is the development of performance assessment activities to benefit from the preclosure risk assessment methodology program. A secondary objective is to use the information developed in this activity to assist in refining the site data parameters list for SCP Issue 2.2 (Performance Assessment Activities 2.2.1.1 and 2.2.2.1, see Section 6.4.1 of this progress report).

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997.

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6.5 ACCIDENTAL RADIOLOGICAL RELEASES (SCP SECTION 8.3.5.5)

SCP Section 8.3.5.5 addresses Issue 2.3, which asks whether the repository can be designed, constructed, operated, closed, and decommissioned in such a way that credible accidents do not result in projected radiological exposures of the general public and of workers in excess of applicable limiting values.

The proposed rule change to 10 CFR Part 60 defines two categories of design basis events. Category one events are those that are reasonably expected to occur during the life of the facility. Category two design basis events are the unlikely but credible events that under the "old" definitions were referred to as accidental radionuclide releases. These design basis events are discussed in Section 4.2 of this progress report. Most work reported here was undertaken to support the classification analysis for items important to radiological safety that have to use the same event identification and consequence analysis for the assessment of safety issues.

Forecast: The primary focus will be the evaluation of radiological dose consequences of category two design basis events to support the viability assessment, the development of Chapter 7 of the Project Integrated Safety Assessment, and development of the Q-list of items important to radiological safety (DOE, 1994c).

6.5.1 Performance Assessment Activities 2.3.1.1 and 2.3.2.1 - Refinement of Site Data Parameters Required for Issue 2.3

The objective of this activity is to refine the population, agricultural, surface-water, and meteorological data needed (a) for determining credible accident sequences and their respective frequencies, (b) for developing candidate design basis accidents, and (c) for determining preclosure radiological exposures to members of the public and to workers as a result of credible accidental radiological releases. This information is collected as part of the environmental, geological, and hydrological site programs described in Chapter 3.

The only item identified as a potential problem in the last progress report (maximum wind speed) has been studied by the Environmental Group. This activity should be reported in the next period.

Forecast: Only minimal activity is expected.

6.5.2 Performance Assessment Activity 2.3.1.2 - Determination of Credible Accident Sequences and their Frequencies Applicable to the Potential Yucca Mountain Repository

The objective of this activity is to develop a comprehensive list of accidents that are both credible and applicable to a potential Yucca Mountain repository.

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To determine the set of events for consideration as design basis events (and thus credible accidents for category two design basis events), potential hazards at the potential repository were identified (CRWMS M&O, 1996u). The work considered a comprehensive list of possible events, both internal and external initiating events, that were then screened for relevancy to radioactive releases at the potential repository. See Sections 4.2, 6.1, and 6.3.2 of this progress report for additional details.

Forecast: No activity is planned unless any amendments are required to the published list of potential hazards.

6.5.3 Performance Assessment Activity 2.3.1.3 - Development of Candidate Design Basis Accidents for the Potential Yucca Mountain Repository

The objective of this activity is to develop a set of candidate design basis accidents to be analyzed as part of the total safety analysis.

The set of credible events identified in the hazards analysis discussed in Section 6.5.2 of this progress report is currently being reduced to a set of candidate design basis events (under the proposed NRC rule change, design basis events embrace all design basis accidents, and in the interest of clarity, the term design basis accident is no longer used). At present, the existing candidate design basis events are being grouped by potential release magnitude or consequence severity to identify the bounding design basis event in each group. To further help identify possible issues in this process of design basis event definition, a small subset of the candidate design basis events is being evaluated in a pilot analysis (see Section 6.5.4 of this progress report).

Forecast: This work will be ongoing in the next period.

6.5.4 Performance Assessment Activity 2.3.2.2 - Consequence Analyses of Credible Accidents at the Potential Yucca Mountain Repository

The objective of this activity is to determine the consequences of credible accidents in terms of radiation doses to the essential repository workers and the public.

In support of the classification analysis of items important to radiological safety as well as site suitability evaluation, several analyses have been undertaken. Bounding radionuclide release terms were developed for the waste forms and have been published (CRWMS M&O, 1996v). Pilot consequence analyses are in progress (and should be reported by the end of the fiscal year) for both the surface and subsurface portions of the repository to evaluate whether the consequences from the events selected (e.g., fuel assembly drop, waste canister drop, mechanistic release from a waste package) are within regulatory limits for the public (see Section 6.3.2 of this progress report). These analyses are using results previously accepted by the NRC, such as

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radionuclide release terms, atmospheric dispersion factors, filter efficiencies, dose conversion factors, and breathing rate.

Forecast: Additional radiological dose consequence analyses will be performed as the set of design basis events is identified from the list of candidates events.

6.5.5 Performance Assessment Activity 2.3.2.3 - Sensitivity and Importance Analyses of Credible Accidents at the Potential Yucca Mountain Repository

The objectives of this activity are (a) to quantify uncertainties and sensitivities in the accident risk assessment and (b) to establish importance rankings for systems, structures, and components of a potential Yucca Mountain repository with respect to radiological safety.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No activity is expected on this task.

6.5.6 Performance Assessment Activity 2.3.2.4 - Documentation of Results of Safety Analyses and Comparison to Applicable "Limiting" Values

The objectives of this activity are (a) to produce documentation of the results of the accident risk assessment in the necessary format and (b) to make comparisons of the results to applicable limiting values. This activity will complete the resolution of SCP Issue 2.3 at the end of the license application design.

The pilot analyses (surface and subsurface) to quantify the radiological consequences for the initial set of events considered as design basis events should be published in the next reporting period. The report of the preliminary hazards analysis and the "design basis" fuel have already been issued, as described in Section 6.3.2 of this progress report.

Forecast: Radiological dose consequence analyses will continue.

6.6 HIGHER-LEVEL FINDINGS - PRECLOSURE RADIOLOGICAL SAFETY (SCP SECTION 8.3.5.6)

SCP Section 8.3.5.6 addresses Issue 2.5, which asks whether the high-level findings required by 10 CFR Part 960 can be made for the qualifying condition of the preclosure system guideline and the qualifying and disqualifying conditions of the technical guidelines for population density and distribution, site ownership and control, meteorology, and offsite installations and operations.

The DOE developed a draft Notice of Proposed Rulemaking to amend 10 CFR Part 960 by adding a new site-specific subpart for Yucca Mountain. The proposed amendment would, in part, eliminate evaluation of the discrete technical guidelines under this system guideline and the system guideline would be superseded by a new preclosure radiological safety system guideline. A determination of compliance with the new system guideline would form part of the basis for evaluating the suitability of the Yucca Mountain site for development as a repository.

Forecast: The Notice of Proposed Rulemaking will be published in the Federal Register and enter a period of public comment and public hearings. Following resolution of the public comments, the amended regulation will be submitted to the NRC for concurrence. A final rule is expected in late FY 1997.

6.7 HIGHER-LEVEL FINDINGS - EASE AND COST OF CONSTRUCTION (SCP SECTION 8.3.5.7)

SCP Section 8.3.5.7 addresses Issue 4.1, which asks whether the higher-level findings required by 10 CFR Part 960 can be made for the qualifying condition of the preclosure system guideline and the qualifying and disqualifying conditions of the technical guidelines for surface characteristics, rock characteristics, hydrology, and tectonics.

The DOE developed a draft Notice of Proposed Rulemaking to amend 10 CFR Part 960 by adding a new site-specific subpart for Yucca Mountain. The proposed amendment would, in part, eliminate explicit evaluation of the discrete technical guidelines under this system guideline. The noncomparative aspects of this system guideline would be evaluated within the preclosure system guideline of the new subpart. No explicit higher-level findings would be required for these guidelines for Yucca Mountain under the proposed amendment.

Forecast: The Notice of Proposed Rulemaking will be published in the Federal Register and enter a period of public comment and public hearings. Following resolution of the public comments, the amended regulation will be submitted to the NRC for concurrence. A final rule is expected in late FY 1997.

6.8 STRATEGY FOR POSTCLOSURE PERFORMANCE ASSESSMENT (SCP SECTION 8.3.5.8)

SCP Section 8.3.5.8 addresses the development of the postclosure performance assessment strategy for resolving Key Issue 1. This issue asks whether the MGDS at Yucca Mountain will isolate the radioactive waste from the accessible environment after closure in accordance with the requirements of 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191. Postclosure performance assessment activities have been revised in anticipation of possible new U.S. Environmental Protection Agency standards for Yucca Mountain.

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Activities during the reporting period concentrated on sensitivity studies in preparation for the total system performance assessment planned for FY 1997 and 1998 in support of the viability assessment. Process model abstractions were derived and evaluated to provide input for overall system performance simulations. A performance allocation study was conducted to test several of the hypotheses of the waste containment and isolation strategy (DOE, 1996o) in order to arrive at priorities for process model improvements and associated needs from site characterization and MGDS design. The full set of FEHMN reports (Dash et al., 1995; Zyvoloski et al., 1995a and b), issued a year ago, were being revised to address comments and all quality assurance (QA) requirements.

6.8.1 Performance Allocation and Hypothesis Testing

The objective of performance allocation and hypothesis testing is to evaluate the relative importance of major components of the natural and engineered system with respect to meeting regulatory requirements (10 CFR Part 60 and potential revisions) and to test the hypotheses of the DOE waste containment and isolation strategy (DOE, 1996o).

Sensitivity analyses were conducted to evaluate the relative and absolute performance of the total system and how this performance varied with location of the major system components along radionuclide transport paths (CRWMS M&O, 1996hh). The allocation of overall repository performance to different components or barriers is of special interest because it aids in prioritizing testing and analysis activities. In this context, performance means the ability of the system or component to isolate the radioactive waste from the accessible environment or reduce the amount of radioactive waste that eventually does reach the accessible environment. The purpose of this performance allocation document was to provide specific sensitivity analyses that show how performance may be allocated amongst the various engineered and natural barriers at Yucca Mountain, depending on uncertainties in knowledge of processes and parameters that control the behavior of these barriers. Special attention was given to the correlation between performance allocation and DOE's waste containment and isolation strategy.

The term "performance allocation" is defined in the SCP (DOE, 1988) in the context of an issues-based hierarchy designed to ultimately determine which information should be collected by the Project to license the site as a nuclear waste repository. Because these issues are "compliance-driven," all the requirements for information were determined by the regulations in effect during the time the SCP was written. The SCP compliance strategy and performance allocation approach are no longer relevant because (a) these regulations are expected to change, (b) understanding of the natural barriers has changed from the SCP assumptions, and (c) the waste package and repository design has changed from the SCP conceptual design. The compliance strategy is being replaced by DOE's waste isolation and containment strategy and by the following performance allocation approach.

The allocation of performance amongst the different components of the overall waste disposal system has been the desired goal of a number of analyses conducted over the past several years. For the most part, these analyses as documented in previous total system

performance assessment iterations in 1991, 1993 and 1995 (Barnard et al., 1992; Eslinger et al., 1993; Andrews et al., 1994; Wilson et al., 1994; CRWMS M&O, 1995a) have identified the key conceptual models and parameters that significantly affect the predictions of postclosure performance. The results, conclusions and recommendations of these previous total system performance assessment analyses (as well as other performance assessment analyses of individual components of the overall system, such as the geosphere performance as exemplified in the ground-water travel time analyses and the engineered barrier performance as embodied in analyses of releases from the engineered barrier system) have been used to shape the present waste containment and isolation strategy. These previous analyses have been instrumental in developing a prioritized list of process models and elements of these process models that are believed to be important in developing a robust safety argument for the viability assessment.

Performance allocation was determined by examining the absolute performance of the various natural and engineered barriers with respect to each other and with respect to overall repository performance. The absolute performance measures were either cumulative radionuclide mass or radiation doses associated with the dissolved radionuclide concentration at the downstream (with respect to the direction of water flow) boundaries of the various barriers. The physical boundaries chosen as representative of the barriers were (from the waste form to the biosphere): (a) the edge of the waste package, (b) the edge of the emplacement drift (i.e., the edge of the engineered barrier system), (c) the base of the TSw, (d) the base of the unsaturated zone, and (e) the edge of the accessible environment at the location of ground-water extraction before entering the biosphere. The calculations were performed with the total system performance assessment software RIP (Repository Integration Program) (Golder, 1995, 1996).

The sensitivity analyses were then used to illustrate the importance of several key hypotheses of the waste containment and isolation strategy. If these hypotheses can be verified, then a robust prediction of long-term performance can be ensured for the viability assessment. To the extent that these hypotheses remain open or uncertain over the next few years, the analyses of performance in the viability assessment will also be uncertain.

Earlier total system performance assessment and subsystem performance assessment analyses have relied on a hypothesis-testing approach to evaluate the relative and absolute significance of alternative conceptual models. Parameter uncertainty has generally been treated in a Monte-Carlo type approach in which the impact of the uncertainty in each parameter on various measures of system performance can be directly quantified using statistical post-processing techniques. The combination of the sensitivity and uncertainty analyses have been extremely valuable in identifying the key postclosure performance related issues that need to be addressed in the viability assessment.

Although the previous total system performance assessment and subsystem analyses have provided many useful insights into the overall system behavior, and have also identified the key conceptual models and parameters that most significantly affect the predicted results, these analyses cannot be used directly to identify how the performance should be allocated amongst the different components of the system. None of the previous analyses have applied a common measure of performance at different locations in the system. To appropriately allocate the

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performance, the predicted performance of each component (or barrier) was compared with the overall system performance.

Uncertainties in each of the key hypotheses contained within the waste containment and isolation strategy have been identified in the previous total system performance assessments. The significance of some of these uncertainties on total system performance has also been evaluated in these assessments. The present performance allocation analyses extend the previous analyses by continuing to stress several of the key uncertainties (which are directly related to the hypotheses in the waste containment and isolation strategy as well as to NRC Key Technical Issues), while at the same time evaluating the absolute and relative contribution to overall system performance given these uncertainties. The following paragraphs summarize the evaluation of the key hypotheses in the waste containment and isolation strategy and the significance of these hypotheses to the overall system performance.

1. Percolation at repository depth is significantly less than net infiltration. This hypothesis was evaluated using a uniform percolation rate at the repository horizon varying from 0.2 to 1.25 mm/yr. In addition, "fast path" percolation through fractures was analyzed for surface water infiltration rates up to 10 mm/yr. These percolation fluxes are currently under scrutiny, as the average has been indicated to be significantly higher than the uniform rate used for this analysis. Reducing the uncertainty in the percolation rate remains one of the highest priorities for postclosure performance. The percolation rate significantly affects
 - Radionuclide releases from the engineered barrier system (decreased percolation yields a decreased likelihood and amount of advective seepage through the engineered barrier system).
 - Advective radionuclide transport through the unsaturated zone (the distribution between fracture and matrix flux is proportional to the percolation rate and the travel time through the unsaturated zone is dependent on the percolation rate).
 - Radiation doses in the accessible environment (because of effects on radionuclide releases from the unsaturated zone to the saturated zone, and the dilution in the saturated zone).

As noted in the introduction to this chapter, Project results indicate percolation fluxes at repository level may be higher than previous estimates. Performance Assessment issued preliminary evaluations of the effect of higher fluxes at the Advisory Committee on Nuclear Waste meeting in September 1996 and at the Nuclear Waste Technical Review Board meeting in October 1996. Analyses of the higher flux effect on performance is ongoing.

2. Fracture flow occurs within a limited volume of the repository host rock at any given time. This hypothesis was evaluated by an alternative assumption to address the possibility of a certain fraction of the host rock conveying significant fracture flow.

In all instances in which the fracture flow percentage was markedly increased from the nominal values in Total System Performance Assessment - 1993 (Andrews et al., 1994; Wilson et al., 1994) or Total System Performance Assessment - 1995 (CRWMS M&O, 1995a), the increased fracture flux resulted in reduced travel times through the unsaturated zone and therefore an increased likelihood of obtaining significant releases and doses at the accessible environment boundary in the first 10,000 years after repository closure. These results reemphasize the need to focus the site characterization program on ascertaining the distribution and magnitude of localized fracture flow in the repository block. Interestingly, although the 10,000-year predicted performance can be markedly degraded given the possibility of localized fast flow paths, the 1,000,000-year performance is not affected significantly.

3. Seepage into the emplacement drifts will be limited to a small fraction of the incident percolation due to capillary forces. This hypothesis was evaluated by examining a range of alternative conceptual models for the likely seepage into the emplacement drifts given a range of possible percolation values. As might be expected, decreasing the seepage percentage of the total percolation results in significantly reduced releases from the engineered barrier system. At the extreme, the seepage flux could be considered zero for reasonable ranges in infiltration. Although this scenario was not investigated in the performance allocation analyses, results of this case were documented in Total System Performance Assessment - 1995. Once again, this hypothesis illustrates the significance of better characterizing the likely distribution of percolation within the host rock and seepage into the emplacement drifts.
4. Bounds can be placed on thermally induced changes in seepage rates. This hypothesis was not directly evaluated in the performance allocation analyses conducted in this study because the primary impact of the thermal hydrology was on the in-drift thermal-hydrological conditions affecting waste package containment and engineered barrier system release (namely, the relative humidity, temperature, and liquid saturation of the invert materials). However, the magnitude of the seepage into the emplacement drifts at the time the waste packages have been breached directly affects the engineered barrier system release. The issue is then whether or not the thermally induced changes in seepage rates still persist several thousand years after emplacement. This issue requires additional analyses.
5. Impacts of climate change on seepage rates can be bounded. Although uncertainties remain with respect to surface water infiltration rates resulting from future climate change, the effects of assumed infiltration rates on seepage rates into emplacement drifts can be bounded, subject to the limitations of the current conceptual models for unsaturated fluid flow. Climate change has been considered in all analyses of the performance allocation study by evaluating surface water infiltration rates ranging from 0.01 mm/yr to 10 mm/yr with different conceptual models for the interactions between porous matrix flow and discrete fracture flow. The results indicate that the relative performance of the analyzed natural and engineered barrier components is not affected significantly for this range of infiltration rates and the resulting seepage rates

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into emplacement drifts. The absolute performance of the components will be affected, however, as summarized for the first three hypotheses. Higher surface water infiltration will result in higher seepage rates into emplacement drifts, for any of the conceptual flow models assumed, which in turn will result in higher radionuclide releases from the engineered barrier system, increased radionuclide transport through the unsaturated and saturated zone, and higher radiation doses in the accessible environment. [Note: The recent estimates of future infiltration flux are higher than the range studied. The results of such higher fluxes are unknown.]

6. Heat produced by emplaced waste will reduce relative humidity in the vicinity of waste packages. This hypothesis was not evaluated in this document because it was presented in the Engineered Barrier System Performance Requirements Systems Study Report (CRWMS M&O, 1996s) obviously delaying the onset of corrosion by reducing the relative humidity for extended periods of time can have significant benefits for waste package containment over the first 10,000 years. These results must be reexamined in light of the recent percolation flux information previously described.
7. Corrosion rates are very low at low relative humidity, and corrosion of the inner barrier is slow. This hypothesis was evaluated using both alternative conceptual models of galvanic protection and alternative designs (namely the thickness of the corrosion allowance material). The results based on low infiltration rates illustrate containment alone can be potentially significant to overall system performance over the 10,000-year time period. Although the significance of the waste package barrier is decreased at longer times, it still can play a significant role in isolating a fraction of the radionuclide inventory from the biosphere for periods exceeding 10,000 years, if the degradation rates are low. Because this barrier is so important, especially over the likely 10,000-year period of regulatory concern, increased emphasis must be placed on confidently confirming the corrosion models used to predict the degradation of the waste packages. The results must be reexamined in light of the recent percolation flux information previously described.
8. Double-walled waste packages will significantly increase containment times due to protection of the inner barrier by the outer barrier. The role of galvanic protection of Alloy 625 (ASTM B 443) as the preferred corrosion-resistant material for the reference waste package design (CRWMS M&O, 1996h) is important for system performance in 10,000 years. Furthermore, the recent estimates of percolation flux are higher than the analyses represented in this hypothesis and galvanic protection may become even more important to performance.
9. Radionuclide release from waste forms due to surface area exposed, dissolution, colloid formation, and microbial activity will be low. The presence of the cladding effectively reduces the available inventory for release and transport by about a factor of 100. In addition, by using alternative assumptions about the controlling phase for neptunium solubility, the peak neptunium dose (which generally occurs at times

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significantly greater than 10,000 years) can be significantly reduced. Both of these factors may be considered additional factors of safety and as such do not require the level of confidence that some of the other hypotheses necessitate.

10. Transport properties of both engineered and natural barriers will significantly reduce radionuclide concentrations due to depletion, diffusion, and dispersion. This hypothesis was not tested exhaustively, but the analyses performed using low percolation flux values illustrate the significance of radionuclide transport, especially over the 10,000-year time period. The effect of the recent information indicating high percolation fluxes is being evaluated.
11. Flow in the saturated zone is much greater than the flow contacting the waste. This hypothesis was evaluated using revised estimates of Darcy flux values in the saturated zone as well as an alternative definition of the location of the critical population. Although the saturated zone contributed minimal performance to the cumulative radionuclide release performance measure, the performance allocation sensitivity analyses clearly indicate that the dilution potential in the saturated zone is a dominant contributor to the prediction of peak doses. Therefore, the confidence in models of flow and transport in the saturated zone must be enhanced to provide more defensible estimates of the dilution potential.
12. Water percolating down through the repository horizon to the water table mixes with the flow in the aquifer. This hypothesis was addressed with hypothesis 11.
13. The amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years. This hypothesis was not addressed in the performance allocation analyses.
14. The severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse. This hypothesis was not addressed in the performance allocation analyses.
15. Volcanic events within the controlled area will be rare and the consequences of volcanism will be acceptable. This hypothesis was not addressed in the performance allocation analyses.

The results of the performance allocation analyses and hypothesis testing were used to establish priorities for developing and testing process models. In turn, this prioritization, given in Table 6-1, provides guidance for prioritizing site and design activities to be conducted in FY 1997 in support of the viability assessment.

Forecast: See Section 6.8.3 of this progress report.

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Table 6-1. Summary of Process Model Development and Testing Priorities for the Total System Performance Assessment for the Viability Assessment

Priority	Process Model
1	Site-scale unsaturated zone hydrological model(s) (ambient)
1	Drift-scale thermal hydrological model(s)
1	Waste package degradation model(s)
1	Site scale unsaturated zone radionuclide transport model(s)
1	Site scale saturated zone flow model(s)
2	Waste-package-scale thermal-chemical model(s) (solubility)
2	Drift-scale radionuclide transport model(s)
2	Site scale saturated zone radionuclide transport model(s)
2	Drift-scale thermal-chemical model(s)
3	Climate-change indirect-effects model(s)
3	Repository-scale unsaturated zone thermal-hydrological model(s)
3	Site-scale unsaturated zone chemical model(s) (ambient)
3	Drift-scale thermal-mechanical model(s)
3	Drift-scale coupled thermal-hydrological-chemical-mechanical model(s)
3	Cladding degradation model(s)
3	Waste form dissolution model(s)
3	Biosphere radionuclide transport model(s)
3	Tectonics direct- and indirect-effects model(s)
3	Volcanic direct- and indirect-effects model(s)
3	Criticality effects model

6.8.2 Model Abstractions and Sensitivity Analyses

The objective of process-level model abstractions and sensitivity analysis is to evaluate the importance of input parameters, including their uncertainties, with respect to the computed output and to derive response functions in terms of tables, curves, and surfaces for input to total system performance assessments.

Unsaturated Zone Percolation

The sensitivity of abstractions of unsaturated zone travel time distributions for conservative solutes to variations in material properties and matrix diffusion coefficients was tested. The thermal-hydrological computer code FEHMN (Finite Element Heat and Mass Transport-Nuclear) (Zyvoloski, 1995) was used for analyzing a one-dimensional column using the three-dimensional unsaturated zone site-scale model (Wittwer et al., 1995). At low infiltration, the unsaturated zone system is dominated by flow in the rock matrix and the rock matrix is undersaturated. Thus, the overall performance is relatively insensitive to the uncertainty and variability of rock matrix properties. At relatively high infiltration, the rock matrix can be saturated and the overall unsaturated-zone system behavior may be highly sensitive

to rock matrix parameter values. Other significant conclusions for abstractions of unsaturated zone flow in the total system performance assessment for the viability assessment included the importance of the van Genuchten parameters (van Genuchten, 1980), matrix diffusion, matrix intrinsic permeability, and fracture properties.

Lateral Unsaturated Zone Flow Diversion

Another aspect of unsaturated zone percolation is the potential for lateral diversion of flow through Yucca Mountain, which was not explicitly modeled in Total System Performance Assessment - 1995. Results of a one-dimensional representation of lateral diversion and abstraction were developed for possible use in future total system performance assessments. The analysis concludes that current information on hydraulic properties of the rocks and fractures at Yucca Mountain indicates there is probably no significant lateral diversion in the unsaturated zone at Yucca Mountain. Although analyses for low surface water infiltration rates predict lateral diversion in the Paintbrush nonwelded hydrologic unit (PTn), the revised higher infiltration rates are expected to result in essentially vertical percolation through this unit to the potential repository horizon. This agrees with the three-dimensional unsaturated zone site-scale model, but additional field data are required to verify this modeling analysis.

Water Dripping into Drifts

Alternative abstractions or conceptual models of the potential for dripping water in the drift were developed, including drip evaporation and "upscaling" of core-measured matrix permeabilities. The intent of these models is to examine the effect of small-scale heterogeneities on dripping water. In particular, they represent the waste package-to-package variability in dripping water. Use of upscaling significantly lowers the dripping flux in fractures at the drift scale. The use of the drip evaporation abstraction additionally reduces the effect of dripping water on repository performance. Both abstractions point to the large effect on performance (radionuclide release at the accessible environment and radiation dose) of the dripping water and therefore the importance of including this process in the process-level models and of developing defensible abstractions for inclusion in total system performance assessments.

Climate Model

The climate model used in Total System Performance Assessment - 1995 is being updated for the total system performance assessment for the viability assessment using a synthesis of additional information regarding climate cycles and other evaluations. Abstractions of some of these data are being developed, including the evaluation of calcite/opal data, the estimation of past percolation using the weeps model (Wilson et al., 1994), and the definition of climate cycles. Results from these ongoing analyses will be abstracted for use in the climate model for the total system performance assessment supporting the viability assessment. Climate variability is an important input to temporal variations in percolation, which is perhaps the most important parameter in the unsaturated zone process-level model abstraction.

Drift-Scale Temperature and Relative Humidity

Thermal-hydrological analyses examined the sensitivity of the drift-scale thermal-hydrological environment to engineered and natural system uncertainties and developed functional relationships (abstractions) that show the dependency of the important state variables (temperature and relative humidity) on these uncertainties (CRWMS M&O, 1996mm). The sensitivity analyses considered two backfill geometries (plus no backfill), two backfill materials, three surface infiltration rates (0.05, 0.3, and 1.25 mm/yr), and three sets of rock properties. The three data sets for the hydrogeologic properties were derived from (a) the preliminary three-dimensional site-scale unsaturated zone model (Wittwer et al., 1995), (b) the Near-Field and Altered Zone Environment Report (Wilder, 1996), and (c) a variation of the report data.

The multiphase flow and transport computer code NUFT (Nonisothermal Unsaturated-Saturated Flow and Transport) (Nitao, 1995) was used for the calculations. The sensitivity analyses examined the influence of parameter and conceptual model uncertainty on thermal-hydrological processes and the relationship between thermal-hydrological processes and such performance factors as dryout, water contact mode, corrosion initiation time, relative humidity, backfill design, and radionuclide mobilization and transport.

The results of the simulations provided abstractions for use in total system performance assessments, in the form of response surfaces of temperature and relative humidity on the waste package surface at the center of the potential repository for each MGDS design alternative. These response surfaces are functions of time and infiltration, taking into account the effects of uncertainty in rock and backfill properties. Response surfaces represent algebraic functions relating the output variables to the input variables of a mathematical model. They are derived from results of multiple runs of the detailed process-level computer codes for a range of values of the input variables. They are usually represented by multi-dimensional tables, which require interpolation to calculate the value of the output variables for specific values of the input variables. [Note: These analyses were performed using lower flux values than are recently indicated. The results may be modified after additional analyses using higher flux values are performed.]

Drift-Scale Thermal-Hydrological Model Dimensionality

The importance of the dimensionality of models used for drift-scale thermal-hydrological analyses was investigated. The dimensionality affects simulated heat transfer processes within the drift and its influence needs to be recognized when abstracting temperature and relative humidity histories for total system performance assessment calculations. A limited number of three-dimensional simulations may be required to help bound the response surfaces developed using two-dimensional simulations. Additionally, the use of "unit cell" analysis is incapable of accurately predicting edge cooling effects. Such analyses must be considered in abstractions developed for thermal-hydrological analyses for future total system performance assessment.

Alternative Heat Transfer Models

A comparison of temperature and relative humidity abstractions using the multiphase flow and transport computer code TOUGH2 (Transport of Unsaturated Ground Water and Heat) (Pruess, 1987; Pruess et al., 1991 and 1996) for different models of heat transfer concluded that use of the radiative heat transfer model produces lower temperatures than using a conduction-only model. An equivalent conduction model, which approximates the effects of radiation, proved comparable to the explicit radiation model and should be a suitable abstraction for use in larger site-scale models. Convection modeling indicated relative humidity near the waste package significantly increases at very early times but decreases after drift wall dryout. These results will be incorporated into the total system performance assessment for the viability assessment because they may have significant impact on waste package degradation.

Waste Package Emplacement

The effect of repository design, in particular the waste-package emplacement design, on abstracted temperature and relative humidity histories was evaluated. The near-field thermal-hydrological process-level model V-TOUGH (Nitao, 1990) was used for the abstractions. The spacing of the waste packages had a significant effect on the temperature and relative humidity, and thus is expected to have a significant effect on performance calculations. The "line-loading" emplacement design appears to produce more favorable performance than the advanced conceptual design, in that it slows corrosion for most of the waste packages and only marginally increases the corrosion rate for the very hottest waste packages. (These waste emplacement designs are described in Section 4.5.2 of this progress report.) Total system performance assessment calculations using the abstracted temperature and relative humidity histories will be performed as this study progresses.

Galvanic Protection and Corrosion Initiation

The waste-package degradation model was modified to evaluate alternative galvanic protection models and alternative corrosion initiation models requiring new abstractions of waste-package failure curves (first pit penetration). The galvanic protection model used in Total System Performance Assessment - 1995 was based on expert elicitation; this model was modified to provide galvanic protection for a shorter time period, which as expected, led to reduced performance of the waste package. The waste package degradation model used in Total System Performance Assessment - 1995 was modified to account for potential mechanisms or materials that may delay the onset of corrosion. The assumed delays decrease the peak radiation dose over 1,000,000 years.

Radionuclide Sorption and Solubility

Additional testing of the abstracted engineered barrier system models was conducted to evaluate the impact on performance. These abstractions included incorporating (a) different radionuclide distribution/sorption coefficients in the concrete invert to delay transport of the radionuclides, and (b) modified solubilities of radionuclides in the engineered barrier system to

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reduce transport of the radionuclides. These assumed engineered changes in the engineered barrier system did not reduce the radiation doses significantly unless the modification maintained its performance-enhancing characteristics for the duration of the analysis. For example, for the 1,000,000-year peak dose, the engineered changes in engineered barrier system material properties must last for nearly 1,000,000 years.

Waste Form Dissolution (including cladding effects)

A cladding failure model for puncture and unzipping was developed and abstractions of the results have been implemented in a total system performance assessment using Total System Performance Assessment - 1995 as the nominal case. The initial model reduced the predicted peak radiation dose over 1,000,000 years by about an order of magnitude.

Other Waste Forms

Abstractions of additional waste forms (various plutonium waste forms, Hanford tank farm waste, and foreign research reactor fuel) were developed and included as additional waste in a nominal case from Total System Performance Assessment - 1995. Alternative dissolution models were used for some waste forms and required additional abstractions over those completed for Total System Performance Assessment - 1995. The results indicate little or no change in repository performance is produced by adding these additional waste forms to the potential repository.

Advective Engineered Barrier System Radionuclide Release

The nominal-case model used for engineered barrier system radionuclide release in Total System Performance Assessment - 1995 included water drips on the waste form, that is, advective water movement through the waste package. This nominal case has been modified so that dripping occurs only on the outside of the waste packages and does not penetrate the waste package because of corrosion products in the pits. This abstraction is believed to be more representative of actual degradation of the waste package.

Unsaturated Zone Radionuclide Transport

As a test of the radionuclide transport abstraction in Total System Performance Assessment - 1995, the breakthrough curves from the assessment were compared with the breakthrough curves from the preliminary site-scale radionuclide transport model (Robinson et al., in prep.[a]). Good agreement was found. In addition, the initial results, current status, and future plans for developing abstractions of the unsaturated zone transport model to match current field observations (chlorine-36) in the ESF were presented. The analyses will take three different approaches and will be conducted to ensure consistency with the site-scale radionuclide transport model. The abstraction of the models using a one-dimensional column will potentially simulate

fast paths in the total system performance assessment for the viability assessment. So far, the sensitivity to infiltration in the range of 1 to 5 mm/yr is found to be much larger than just a linear model would predict. This may be due to the onset of fracture flow in the Calico Hills vitric unit.

Colloid Transport

Models for colloid transport were evaluated to determine the additional capability that may be brought to the analyses and the ease of abstraction. The site-scale radionuclide transport model (Robinson et al., in prep.[a]) does not include colloidal transport. An abstraction of one of the colloid transport models is proposed, which should be implementable in the total system performance assessment for the viability assessment.

Saturated Zone Radionuclide Dilution

Alternative saturated zone discharge scenarios were formulated that cover a range of possible biosphere scenarios (for instance, drinking water withdrawal) that may be required to model the effect of new radiation dose standards. The regional and site-scale numerical saturated zone flow model and transport models (Robinson et al., in prep.[a]) will be incorporated into the saturated zone discharge scenario analysis. An approach to abstraction of the site-scale models would be to derive peak radionuclide concentrations at the potential saturated zone ground-water discharge locations as functions of the more sensitive modeling parameters.

Radiation Doses

Future regulations may require evaluation of radiation doses to individuals at distances greater than the 5-km boundary of the accessible environment used in Total System Performance Assessment - 1995. An abstraction extended the saturated zone to Amargosa Valley, which is assumed to be 30 km from the site boundary. An additional dilution by a factor of 25 was assumed, based on dilution calculations in Total System Performance Assessment - 1995.

Performance Assessment Working Data Set

In previous reporting periods, a performance assessment working data set was assembled for detailed process modeling and total system performance assessments. This data set includes data from site characterization and recent hydrologic laboratory experiments. An update of this data set was completed during the reporting period. In addition to incorporating new data and information appropriate for use in future calculations, a browser-based user interface was also developed and tested. In the future, this interface will allow access to the data set from the Internet and provides links to documentation supporting the data. The latter capability is important to ensure the traceability and reproducibility of data used in subsequent analyses.

Forecast: See Section 6.8.3 of this progress report.

6.8.3 Total System Performance Assessment for the Viability Assessment

The objective of the total system performance assessment for the viability assessment is to support a decision by the OCRWM in 1998 to continue site characterization if the site appears viable for licensing and constructing a geologic repository at the Yucca Mountain Site (DOE, 1996a).

Initial planning for the total system performance assessment in support of the viability assessment was completed (CRWMS M&O, 1996ii) and included in revisions to DOE's Program Plan (DOE, 1996a) and long range plan (a computer data base). The plan intends to achieve as robust an assessment of total system performance as possible with available resources to meet the objectives laid out in the Program Plan. This plan was constructed to ensure the incorporation of the most up-to-date knowledge embodied in current site and engineering process models (and revisions to these process models that result from interpretation and analysis of recently acquired data), as well as the existing uncertainties. This approach focused on the elements identified in the waste containment and isolation strategy (DOE, 1996o).

As identified in the plan, the overall total system performance assessment approach may be broken into the following seven activities:

1. Develop, substantiate, test, and document models of all relevant processes affecting postclosure waste containment and isolation.
2. Identify all relevant uncertainties in the models.
3. Identify all relevant scenarios that will be analyzed in the total system performance assessment. This includes defining the design alternatives that will be evaluated.
4. Conduct sensitivity analyses on each of the process models, evaluating the effects of all of the relevant uncertainties. This is a collaborative effort between the performance assessment organization and the process model development organization.
5. Abstract the relevant results from the process models (including the uncertainty) to provide input to the total system model.
6. Conduct total system analyses that will predict performance as a function of all relevant scenarios, alternative models, and parameter uncertainty and variability.
7. Document all assumptions, results, and conclusions.

The first two activities are joint responsibilities of site, design and performance assessment organizations. The remaining activities are the responsibility of the performance assessment organization. The first five activities are planned for FY 1997, while the remaining two activities are planned for FY 1998.

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In this plan, the overall system performance assessment includes the following processes:

1. Waste form degradation
2. Radionuclide mobilization
3. Waste package degradation
4. Near-field environment
5. Thermal-hydrology
6. Unsaturated zone flow
7. Saturated zone flow
8. Unsaturated and saturated zone radionuclide transport
9. Biosphere radionuclide transport and radiation exposures
10. Disruptive features, events and processes.

For each of the ten processes, the plan describes the following:

1. Status of abstractions of the relevant process models in previous total system performance assessments
2. NRC's treatment of processes in its recent Iterative Performance Assessment Phase 2 (Westcott et al., 1995)
3. Some of the most relevant uncertainties associated with the current understanding of the process models
4. Existing sources of information with which to substantiate the process models
5. Expected output from the abstraction of each process model
6. Key personnel from both the performance assessment organization and the process model development organizations (and supporting organizations) who can provide fundamental understanding to assist in the successful abstraction of these models for use in the total system performance assessment for the viability assessment
7. Detailed schedule for all abstraction, analysis, and documentation activities.

Forecast: The set of revised FEHMN reports will be issued. Total system performance assessment activities in support of the viability assessment will proceed according to the plan outlined in Section 6.8.3 of this progress report, concentrating on the first five of the seven activities in FY 1997: process modeling, uncertainty and sensitivity evaluations, scenario identification, and process model abstractions. The last two of the seven activities, the total system analyses and the documentation, are planned to be performed in FY 1998.

6.9 CONTAINMENT BY WASTE PACKAGE (SCP SECTION 8.3.5.9)

SCP Section 8.3.5.9 addresses Issue 1.4, which asks whether the waste package will meet the performance objective for containment as required by 10 CFR 60.113.

Waste package container designs, as described in the Controlled Design Assumptions Document (CRWMS M&O, 1996e), currently focus on a multibarrier approach and include families of materials other than the copper-base materials and the iron to nickel-base "austenitic" materials that were the subject of the SCP conceptual design (SNL, 1987). The only option of these "alternate materials" currently being pursued is the "bimetallic/single metal," which is the multibarrier design in the advanced conceptual design report (CRWMS M&O, 1996b). Thus, progress on evaluating these "alternate materials" is discussed under Performance Assessment Activity 1.4.2.4 (Section 6.9.6) and Performance Assessment Activity 1.4.3.3 (Section 6.9.9).

6.9.1 Performance Assessment Activity 1.4.1.1 - Integrate Design and Materials Information (Metal Container)

The current waste package container designs focus on a multibarrier approach for both spent nuclear fuel packages and for vitrified high-level waste packages. These designs are robust in the sense that (a) multibarriers provide reinforcement to the containment function, (b) thick sections are used for some of the barrier materials, and (c) some of the barrier materials are very highly resistant to corrosion under a wide range of environmental conditions.

Volume 3 of the Engineered Materials Characterization Report was revised (McCright, in prep.) to include the results of testing and modeling activities that have occurred since the report was originally issued in December 1994 (Van Konynenburg and McCright, 1995). Volume 1 (on the background and history of the engineered barrier system candidate materials) and Volume 2 (on the physical and mechanical properties of the candidate materials) were not revised. The engineered barrier system testing and modeling work has been discussed in previous progress reports, and results obtained in this reporting period are discussed in Sections 6.9.6 and 6.9.9.

Integration between the waste package development effort and the waste package materials effort has continued with technical discussions and exchanges of weekly and monthly progress reports.

Fabrication for Galvanic Protection

The general fabrication techniques for the multibarrier container and how the barriers will be configured were discussed. In particular, fabrication techniques and barrier configuration impact the galvanic interaction between the barriers and the extent galvanic protection provided by the outer barrier can prolong the containment life of the inner barrier. Contact between the metals is an important factor in determining the effectiveness of galvanic protection. For instance, if the two barriers making up the container were clad together, there would be a metallurgical bond between the layers, while at the other extreme, if the two barriers were

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fabricated as separate containers and then slipped one inside the other, the contact between the two metals would be much more casual. If all other factors are the same, the more intimate contact would ensure more effective galvanic protection than the casual contact. Characteristics of the electrolyte, particularly its conductivity, would also play a role in determining the effectiveness of galvanic protection.

A weld-clad process has also been considered, in which the inner barrier material would be deposited in multiple passes from welding electrode material. This process has been performed on some of the nickel-chromium-molybdenum candidate alloys but it does not appear feasible for titanium. The process is also expensive. In addition to the "slip-fit" configuration of two separately fabricated concentric containers, a "shrink-fit" arrangement by heat treating the two separate containers is being evaluated. This process ensures a reasonably intimate bond between the two metals over a large fraction of the surface area. The contact area between the two materials making up the galvanic couple is an important materials test parameter, so useful information will be obtained from and shared with the waste package design group to evaluate container fabrication processes.

Addition of Alloy 625

Alloy 625 (ASTM B 443), a nickel-chromium-molybdenum alloy, was added to the corrosion testing program (CRWMS M&O, 1996h). This alloy was one of the materials used in evaluating the weld clad technique for fabricating a two-metal container and has been used in many corrosion applications, both in aqueous media and in higher temperature, often polluted, atmospheres. Alloy 625 is often used for making filler welds in other high-nickel alloy and is considered one of the most weldable alloys in this class of materials. The alloy contains an intermediate level of molybdenum (8 to 10 percent) compared with the other candidate materials, Alloys 825 and G-3 (3 to 6 percent) and Alloys C-22 and C-4 (14 to 16 percent), and consequently its localized corrosion resistance in very aggressive environments would also be expected to be intermediate.

Backfill Study

Input was provided to the backfill section of the draft Engineered Barrier System Performance Requirements Study Report (CRWMS M&O, 1996s). The input concerned the effects of chemical additions to the backfill to buffer the pH and Eh of the environment. Specifically, the study considered addition of lime (CaO) to the backfill to control the pH to a more alkaline value and thereby reduce corrosion effects on the container material, and the addition of either iron (Fe) metal (in a powdered form) or magnetite (Fe₃O₄) to control the Eh of the environment. While control of the reduction-oxidation condition in the environment may mitigate some corrosion effects, the principal reason for adding the reducing agents is to control the oxidation state of radionuclides, especially neptunium to render it less mobile and therefore less likely to be released from the engineered barrier system. Additionally, added lime would react with carbon dioxide (CO₂), including any ¹⁴CO₂ escaping from the waste package, to form insoluble calcium carbonate (CaCO₃).

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The study evaluated the long-term effects of the chemical additives by using the EQ3/6 geochemical code (Wolery, 1992a and b) to estimate the pH, Eh, mineral assemblage, and water chemistry as a function of time. Also, the OS3D/GIMRT reactive transport code (Steefel and Yabusaki, 1995) was used to simulate chemical changes in an aqueous fluid as it moves through a porous medium. This code provides a model of the time-dependent evolution as a function of flow rate, thermal gradient, and water chemistry. Different ground-water chemistries were used to model the reaction over a range of chemical conditions. Moreover, the study considered whether the drifts housing the waste packages would be "open" or "closed" with respect to circulation of atmospheric gases, particularly CO₂ and O₂, that would be expected to influence the pH and Eh of the environment. The study focused on a backfill composed of magnetite, lime, and quartz sand in the molar ratio of 80:15:5. Quartz sand was considered as the primary backfill material because it has no internal porosity (compared with crushed Topopah Spring tuff) and will therefore not "wick" water to the waste package.

The conclusion from the study was that the chemical additives to the backfill, even when added in generous proportions, were not effective in modifying the environment for the time periods when they would be needed. The reaction with atmospheric gases during the "thermal period" when the repository is hot and dry consumes the additives so that when the repository cools and becomes more humid, not enough material remains to condition the aqueous-dominated environment. The code simulations demonstrated that a backfill composed of magnetite, lime, and quartz sand will not control oxygen fugacity and pH unless the drifts are completely sealed. Even then, the chemical conditioning effects would be minor and would probably not achieve the engineering goals. Substituting elemental iron, as a powder, for magnetite gave essentially the same results. All the chemical evolution takes place and the conditioners are expended within a matter of decades, which is insignificant with respect to the repository time frames.

Performance Confirmation Concept Study

Input was provided for the waste package section of the Performance Confirmation Concepts Study Report (CRWMS M&O, 1996jj). Previously, several key parameters were identified as those parameters that needed to be measured during the repository operational period and that would lead to increased confidence in the performance of the repository and engineered barrier system (see Section 6.16). The key parameters covered different measurements of corrosion and degradation of the waste package container, as well as the waste form and other internal parts of the waste package. The input covered the different approaches for waste package confirmation testing (which would proceed after repository construction), how each testing approach would resolve some uncertainty of waste package performance, and the comparative costs of each testing approach. The following five testing approaches were recommended in the report.

1. Continuation of laboratory measurements "offsite". This approach involves the continued testing of "laboratory size" specimens of the container materials to gain long-time exposures (perhaps 10 years or more) under meaningful repository conditions. Some limited testing of the waste forms will also continue to gather time-

dependent information on their degradation modes. The major advantages of the laboratory tests are that the test conditions are controlled and that a range of conditions (beyond those available in the repository with newly emplaced containers) can be used, including those that simulate conditions expected to occur hundreds to thousands of years after emplacement.

2. In situ monitoring. This approach involves monitoring of critical physical and chemical parameters within the repository to detect conditions that may indicate that significant degradation will occur (e.g., humidity rises above a critical value) or that a container may have breached (e.g., detection of a radioactive "sniffer" gas).
3. Pull radioactive waste packages and perform measurements onsite or offsite. This approach involves removing a real waste package from the repository and examining it, most likely using a combination of nondestructive and destructive techniques. This approach would provide a "window of opportunity" where countermeasures could be taken if a waste package was severely damaged or showed signs of significant degradation. Examination of the container, waste form, and criticality control and other internal structure would provide a definitive picture of the status of each component.
4. Pull dummy waste packages and perform measurements onsite or offsite. This approach involves emplacing "dummy" waste packages in different locations in the repository for the sole purpose of withdrawing and examining them at a future date. The dummy waste packages would have the same dimensions and configuration as the real waste packages, but would contain heating elements to simulate a thermal environment. Examination of these waste packages, however, will reveal information only about the containers.
5. Use specimens and perform measurements onsite or offsite. This approach involves placing test specimens of the container materials in different locations in the repository, as a kind of "witness" specimens. These specimens would be examined at future periodic intervals for evidence of corrosion and other degradation. Specimen size would range from laboratory scale to dimensions approaching those of the container (e.g., waste package diameter cylindrical rings containing welds). This approach is viewed as intermediary between the laboratory testing and using dummy waste packages.

Input to the report was also provided on the comparative merits of these approaches and the ways in which each approach would resolve uncertainties in performance. The report also discussed the frequency at which measurements would be made and how this affects the confidence in the performance predictions. The report then estimated approximate costs for the approaches and the different levels of confidence. However, the report did not specifically recommend which testing approach or approaches should be used.

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Forecast: Close interaction between the waste package development and waste package materials organizations will be maintained through informal and frequent reporting and discussion. More formal periodic meetings are planned. To respond to recent developments, the effect of contact areas between the inner and outer barrier materials will be incorporated into experimental designs for galvanic corrosion testing. Specimens of Alloy 625 will be procured and added to the testing activities, where appropriate. Formal review and publication of the Engineered Materials Characterization Report is planned for the early part of FY 1997. Any additional and available testing information will be added. As needed, the waste package materials organization will support systems engineering in the formal review and modification of the reports on the evaluation of the backfill option and on the performance confirmation test requirements.

6.9.2 Performance Assessment Activity 1.4.1.2 - Integrate Design and Materials Information (Alternate Barriers Investigation)

The purpose of this task is to characterize the behavior of nonmetallic materials, such as ceramics, and to determine degradation rates and mechanisms. One of the barriers of the disposal container may be fabricated from a nonmetallic material. A primary objective of this activity is to determine the feasibility of making a nonmetallic barrier part of a waste package.

Subactivity 1.4.1.2.1 - Survey of alternative barrier designs, materials, and processes to determine feasibility of fabricating a satisfactory waste package. No progress was made during the reporting period; this was an unfunded activity.

Forecast: Although the effort in evaluating ceramic and other nonmetallic materials was curtailed in FY 1995 and FY 1996, there is interest in reviving the work. Plans have been made for FY 1997 to evaluate thermal spray coatings of alumina and an alumina-magnesia spinel on metal substrates. This work follows from the survey report on materials and fabrication processes (Wilfinger, 1995). The evaluation will consist of making coated specimens and measuring their mechanical properties, bonding to the substrate, and degree of porosity in the ceramic. The specimens will also be exposed to aggressive but repository-relevant environments to measure the corrosion protection offered by the ceramic coating.

6.9.3 Performance Assessment Activity 1.4.2.1 - Selection of the Container Material for the License Application Design

The objective of this activity is to select the container material for more detailed characterization of its properties relevant to attaining the performance objectives of the postemplaced container. This activity involves the metallic materials and ceramic-metal systems, bimetallic/single metal systems, and coatings and filler systems.

Subactivity 1.4.2.1.1 - Establishment of selection criteria and their weighting factors. Previous work established selection criteria and weighting factors for containment barrier

materials only (LLNL, 1995). Completing the selection of waste package materials also requires selection criteria and weighting factors for internal components of the disposal container. These have been developed and applied in a recent deliverable (CRWMS M&O, 1996h). The selection criteria and weighting factors are listed in Table 5-3 and discussed under Subactivity 1.10.2.4.1 in Section 5.1.4 of this progress report. Because the internal components perform functions that differ from those of the containment barriers, it was necessary to define two new selection criteria, thermal performance and neutronic performance.

Subactivity 1.4.2.1.2 - Material selection. The selection criteria and weighting factors discussed above were applied to candidate materials to select materials for viability assessment design. These materials are listed in Section 5.1.4 under Subactivities 1.10.2.4.2 through 1.10.2.4.7 of this progress report.

Forecast: No additional activity on disposal container material selection is planned for the viability assessment design phase, which includes all of FY 1997. Revision of the selection may be necessary, however, if the disposal container design is changed or if significant new information becomes available on the near-field environment or materials degradation.

6.9.4 Performance Assessment Activity 1.4.2.2 - Degradation Modes Affecting Candidate Copper-Based Container Materials

The objective of this activity is to analyze which degradation modes have any significant chance of occurring on the candidate copper-based materials in the postemplacement periods and to perform laboratory testing and analysis activities to provide information for modeling the rate of degradation of the container materials (Performance Assessment Activities 1.4.3.1, 1.4.3.2, and 1.4.3.3, see Sections 6.9.7, 6.9.8, and 6.9.9 of this progress report).

Current designs, as described in the Controlled Design Assumptions Document (CRWMS M&O, 1996e) focus entirely on multibarrier waste package container configurations; therefore, degradation mode activities are reported under Performance Assessment Activity 1.4.2.4 in Section 6.9.6. The only option currently being pursued under the controlled design assumptions is the "bimetallic/single metal," which is the multibarrier design. See the beginning of Section 6.9.

No progress was made during this reporting period on the eight subactivities within this activity that address the degradation of copper-based materials and related laboratory testing and analysis; these were unfunded activities.

Forecast: See the forecast for Subactivity 1.4.2.4.3 in Section 6.9.6.

6.9.5 Performance Assessment Activity 1.4.2.3 - Degradation Modes Affecting Candidate Austenitic Materials

The objective of this activity is to determine which degradation modes have a significant chance of occurring for the candidate austenitic materials in the postemplacement periods and to perform laboratory testing and analysis activities to provide information for modeling the rate of degradation of the container materials (Performance Assessment Activities 1.4.3.1, 1.4.3.2, and 1.4.3.3, see Sections 6.9.7, 6.9.8, and 6.9.9 of this progress report).

Current designs, as described in the Controlled Design Assumptions Document (CRWMS M&O, 1996e), focus entirely on multibarrier waste package container configurations; therefore, degradation mode activities are reported under Performance Assessment Activity 1.4.2.4 in Section 6.9.6. The only option currently being pursued under the controlled design assumptions is the "bimetallic/single metal," which is the multibarrier design.

No progress was made during this reporting period on the nine subactivities within this activity; these were unfunded activities. The single exception is the inclusion of stainless steels in the test matrix for stress corrosion cracking (see Section 6.9.6).

Forecast: See the forecast for Subactivity 1.4.2.4.3 in Section 6.9.6.

6.9.6 Performance Assessment Activity 1.4.2.4 - Degradation Modes Affecting Ceramic-Metal, Bimetallic/Single Metal, or Coatings and Filler Systems

The objective of this activity is to evaluate potential degradation modes that can affect an alternative waste package container developed under the alternate barrier investigations and to perform the testing needed to quantify and model these degradation phenomena. These degradation phenomena apply to the post-emplacement periods. Laboratory testing and analysis activities are to provide information for modeling the rate of degradation of the container materials (Performance Assessment Activities 1.4.3.1, 1.4.3.2, and 1.4.3.3; see Sections 6.9.7, 6.9.8, and 6.9.9 of this progress report).

All the work discussed in the following subactivities is applicable to the bimetallic/single metal case for design alternatives discussed in the SCP (DOE, 1988).

Subactivity 1.4.2.4.1 - Assessment of degradation modes affecting ceramic-metal systems. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.4.2.4.2 - Laboratory test plan for ceramic-metal systems of the alternate barriers investigations. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.4.2.4.3 - Assessment of degradation modes affecting bimetallic/single metal systems. The objectives of degradation mode surveys are (a) to compile relevant previously

published information about a candidate material and its performance in a number of environments and (b) to interpret this body of information in the context of a potential repository in Yucca Mountain. In many instances, the degradation mode survey indicates the ways in which a material can degrade and serves to indicate the rate and kind of degradation in environments that have some similarity to what a metal barrier may experience in the Yucca Mountain setting. In other instances, the lack of information suggests what work will be required to determine the behavior of the candidate material under Yucca Mountain environmental conditions.

The degradation mode survey on the effects of fabrication and welding on the performance of candidate corrosion-resistant nickel-base and titanium-base alloys (Goldberg and Dalder, in prep.), discussed in Progress Report #14 (DOE, 1996b), has been technically reviewed and will be published shortly.

A degradation mode survey has been prepared on the galvanic corrosion behavior of candidate corrosion allowance materials and candidate corrosion resistant materials for the waste package container design (Roy et al., 1996). The survey cited references on carbon and low alloy steels, copper-nickel and nickel-copper alloys, stainless steels, nickel-rich stainless alloys, nickel-base alloys, and titanium and its alloys. An important item in determining container performance is whether corrosion of the outer barrier serves to protect the inner barrier and for how long this galvanic protection may operate. The efficiency of galvanic protection also depends on how the two barriers are fabricated and how they contact one another, as discussed in Section 6.9.1 of this progress report. The survey based the discussion of galvanic phenomena on the Wagner-Traud mixed potential theory (Jones, 1992) and how this theory may be used in the demonstration of galvanic effects between the metals of interest in the waste package container design. Finally, the survey pointed out the possible complications between an anodic carbon steel and a galvanic nickel-base or titanium-base couple, including formation of ferric ion corrosion products from the steel (could favor pitting and crevice attack, particularly on the nickel-base alloys) and hydrogen evolution on the more cathodic member of the couple (could favor hydrogen embrittlement, particularly on the titanium-base alloys). If a copper-bearing alloy were used as the outer barrier, cupric corrosion products could also favor pitting or crevice attack on a nickel-base inner barrier.

Forecast: The degradation mode surveys will be published. No additional surveys are planned for the immediate future, but welding effects in the corrosion allowance materials should be surveyed at a future date. The welding effects relative to this class of materials appear to be less of a performance issue than they are on the corrosion resistant materials. Several of the technical issues raised in the degradation mode survey on galvanic effects will be addressed in testing activities to resolve these issues as they affect the waste package.

Subactivity 1.4.2.4.4 - Laboratory test plan for bimetallic/single metal material system.

Long-Term Corrosion Studies

The objective of long-term corrosion studies is to determine comprehensive corrosion properties of metallic alloys being considered for constructing the multibarrier waste package

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container. Three classes of materials are to be addressed: corrosion resistant, corrosion allowance, and intermediate. Corrosion properties to be assessed are general corrosion, pitting corrosion, crevice corrosion, intergranular corrosion, stress corrosion cracking, hydrogen embrittlement, and galvanic corrosion. This activity will provide kinetic and mechanistic information about the corrosion degradation of candidate materials. This information will support materials selection, performance analysis, and model development. Tests are conducted in environments that bound the range of environmental conditions and water chemistries that are projected to develop near the container surface over long periods of time. This comprehensive corrosion test is planned to last at least five years, with test specimens periodically removed and inspected to measure corrosion degradation as a function of exposure time.

Activities continued to prepare the facility for the long-term corrosion tests. The first 12 test vessels were installed in the facility and various components were then installed in and on each vessel. These components included two 6-kW heaters in each vessel, a stirrer, a condenser, six test racks, three liquid level sensors, and numerous pieces of hardware, fittings, fasteners, valves, switches and solenoids. The vessels themselves are made from fiberglass-reinforced vinyl ester polymer (Hetron 922). Because this test is under the strictest QA controls, several technical procedures were written on specimen identification, specimen handling, initial characterization of specimens, and test environment formulation. In addition, an individual software plan was written for the software that controls the operation. Testing started in the first 12 test vessels just before the end of the reporting period.

Test specimens were initially characterized by measuring their dimensions and, where appropriate, their weights, and this information was entered automatically into a data base. Several thousand specimens were characterized, representing all the candidate materials. These range from carbon steel to titanium. Additional entries will be made into the data base when the as-corroded specimens are withdrawn from the test environment and recharacterized. Three specimen properties are being characterized: weight loss, crevice geometry, and stressed U-bend. Some specimens contain welds. The test vessels are filled to about 60 percent so that some (about half of the total number) specimens are fully immersed in the water, some are exposed to the saturated vapor space above the liquid, and a few specimens are placed right at the water line. The temperature and liquid level are controlled automatically during the test. An Allen Bradley Programmable Logic Unit was acquired for temperature and liquid level control.

A formal QA readiness review was held in May 1996 to identify items needed to be complete before startup. These were completed during the summer, and a surveillance was held in August 1996 to close out these items. A safety review and a design review were held in August and September 1996. Considerable detail about the long-term corrosion test was given in the draft revision of the Engineered Materials Characterization Report (McCright, in prep.).

Forecast: Of the 12 vessels in this first increment, the first four vessels will contain specimens of corrosion-allowance materials, a 1020-type carbon steel in wrought form, a similar carbon steel in cast form, and a 2.25 percent chromium - 1 percent molybdenum alloy steel. Two of these vessels will be operated at 60°C and two at 90°C. Two will contain low ionic strength water (containing a composite of ions found in UE-25 J#13 well water and other ground waters

at the Nevada Test Site) and the other two will contain a high ionic strength water (with the same ionic ratios). The next four vessels will contain specimens of the nickel-base and titanium-base corrosion-resistant alloys at the same temperatures and water chemistries as the first group. The third group of four vessels will contain the high ionic strength water acidified to a pH just above 2. Two of the vessels will contain the corrosion-resistant materials, and the other two vessels will contain the intermediate materials (70/30 copper/nickel and Monel 400). These tests are scheduled to start imminently. After the tests have operated six months, specimens will be withdrawn and measured and examined for corrosion. The exact analyses will depend on what is observed.

Thermogravimetric Analysis Studies

The objectives of this work are to determine the conditions under which aqueous film corrosion processes occur after emplacement of the waste package and to characterize the mechanistic processes occurring. The conditions of susceptibility to aqueous film corrosion are particularly significant in an unsaturated zone repository, because the extent of degradation of the candidate materials becomes much greater when aqueous processes begin. The key parameters appear to be humidity, temperature, gaseous contaminants, surface contaminants (salts), and surface condition of the metal. The experimental work aims to determine the interrelationship among these parameters. Thermogravimetric analysis is a particularly sensitive technique that uses a microanalytical balance to measure very small changes in weight gain as a material reacts with the environment.

Tests were performed on carbon steel (AISI 1020) specimens with three different surface conditions: clean, polished surfaces; clean, etched surfaces; and salt covered surfaces. Tests were conducted in the 60 to 90°C temperature range over a wide range of relative humidities at each test temperature. As might be expected, the surface condition plays an important role in determining the critical relative humidity. On clean polished surfaces, high relative humidities (>85 percent) were necessary before enhanced corrosion relative to "dry oxidation" over time periods of about 100 hours would be detected. This is consistent with other studies that showed that significant water adsorption does not occur on polished contaminant-free surfaces at relative humidity less than 95 percent. Hence the aqueous film electrochemical corrosion occurs only at high relative humidity under these conditions.

Chemical etching of the surface enhances the susceptibility to electrochemical corrosion at lower relative humidity values. This is probably due to a surface roughening, although residual etching on the surface may have enhanced the susceptibility. In either instance, water adsorption occurred at lower relative humidity values than on a polished surface. At high relative humidity values (85 and 90 percent), the initially high corrosion rate decreased with increasing time. The outer oxide formed on these surfaces was nonadherent, however, the inner oxide was not easily removed.

On salt (NaCl)-covered surfaces, the susceptibility to aqueous film electrochemical corrosion was significantly enhanced relative to the clean surfaces. At about 88 percent relative humidity, the initial corrosion rates were up to 10,000 times faster than on a clean surface under

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similar conditions. The initial corrosion rate decreases with decreasing relative humidity. With increasing time at high relative humidity, the corrosion rate decreased and indeed seemed to plateau within the detectable weight measurement. The same effect is expected at the lower relative humidity values after the corrosion had progressed as much as the high relative humidity. The ineffectiveness of the deposited salt at sustaining the corrosion may be due to "incorporation" of the salt in the oxide layer. With redeposition of salt, the rate may return to its initial rate (testing is planned to investigate this).

Greater details of the thermogravimetric analysis test results were reported in the revised draft Engineered Materials Characterization Report (McCright, in prep.).

Forecast: Future studies will extend the characterization to higher and lower temperatures; in particular, the corrosion susceptibility will be studied at temperatures above 100°C where hygroscopic salts will enhance the adsorption of water. Other factors that may affect aqueous film electrochemical corrosion, such as gas phase contaminants, surface contaminants (such as salts), and surface condition (e.g., previously oxidized, scratched) will also be investigated. Longer term tests will be performed in controlled temperature and humidity chambers. The planned microstructural investigation of the corrosion product formed on the surfaces under the different test conditions will give important information that will help elucidate the mechanism of the corrosion process. This information is necessary for modeling the corrosion process. Planned testing includes identifying the oxide crystal structure and composition and determining the surface morphology.

Crack Growth Tests

The objective of these tests is to evaluate the susceptibilities of candidate corrosion-resistant metallic container materials to environment-assisted embrittlement, including stress-corrosion cracking and hydrogen embrittlement under metallurgical and environmental conditions relevant to the potential MGDS. These test data will then be used in developing predictive models.

As discussed in Progress Report #14 (DOE, 1996b), several double cantilever beam test specimens (NACE Standard TM0177-90) of the corrosion-resistant materials were purchased, as well as test cells and other apparatus for conducting these tests in acidified chloride solutions at 90°C. The mechanical properties of the specimens were determined, because the material yield strength is needed for the fracture mechanics formula to calculate what loads are needed. However, these tests have not yet begun.

Forecast: Remaining items for the double-cantilevered beam specimens will be purchased in FY 1997. Susceptibilities to stress corrosion cracking of six corrosion-resistant candidate materials (Alloys 825, G-3, G-30, C-4, C-22, and Ti Grade 12) will be evaluated by stressing a fatigue precracked double cantilever beam specimen by inserting a double taper wedge. The test is a crack-arrest type of fracture mechanics test for measuring the resistance of metallic materials to propagation of stress corrosion cracking, expressed in terms of a critical stress intensity for stress corrosion cracking (K_{Isc}). Each test is expected to run for several

months. K_{isc} will be computed using the specimen dimensions, the equilibrium wedge load, and the crack length. The crack length measured at the conclusion of each test will provide the crack growth rate data. A selected number of longer term stress corrosion tests will be planned using the results from these shorter term tests.

Microbiologically Influenced Corrosion Studies

The objective of microbiologically influenced corrosion studies is to determine if corrosion is enhanced by the presence and propagation of microorganisms, particularly bacterial species. Metabolic products from these microorganisms can alter significantly the chemical environment and this can occur on a localized level or over a wide area of the container surface. Different microorganisms attack different alloys because of the metabolic diversity of microbial physiology combined with the chemical specificity of the corrosion process. This study surveys microbiologically influenced corrosion effects on the candidate waste package materials.

Testing of carbon steel specimens in microbially inoculated test cells has begun. An electrochemically based system for monitoring of microbial corrosion rates was devised. This system uses test cells assembled from 4-cm diameter, 13-cm long glass flat-bottom test tubes containing R2 media, a low-nutrient formulation (Reasoner and Goldreich, 1985) prepared using artificial pore water, equivalent to the UE-25 J#13 well water at Yucca Mountain (Amy et al., 1992) to simulate the electrolyte present at the Yucca Mountain site. A low concentration (0.5 percent) agar was added to the media such that its final consistency is a semisolid, which somewhat impedes the diffusion of air into the system. Working and counter electrodes were sealed into the cell through a soft rubber stopper. The 1020 carbon steel working or specimen electrode in each cell was a sheet ribbon approximately 5-mm wide, 1-mm thick, immersed to a length of about 10 cm, giving an exposed surface area of 9.7 cm². The 0.5-mm plutonium-wire counter electrode was coiled around the working electrode while avoiding contact between them. The saturated calomel reference electrode was immersed in a second identical test tube containing aqueous 1 percent KCl connected to the test cell through an agar-KCl salt bridge of 1.5-mm polyethylene tubing.

Strains of slime-producing bacteria isolated from the Yucca Mountain microbial community, sulfate-reducing bacteria, and iron oxidizing bacteria were enriched using standard techniques. Each bacterial type was grown separately in its respective media to a standard cell density. Triplicate sterile test cells were inoculated as follows: each type of bacteria individually, paired combinations, and all three types of bacteria inoculated together. Abiotic, sterilized control cells were also prepared in triplicate to evaluate abiotic corrosion effects. The inoculated and abiotic cells were finally sealed around the rubber stoppers with paraffin tape to prevent biological contamination during subsequent long-term exposures.

Polarization resistance measurements were conducted at regular intervals on each cell by conventional potential-scan methods using a potentiometer and accompanying software (Gamry Instruments, Inc., PA). During polarization resistance measurements, potential was scanned from -10 mV to +10 mV at a maximum rate of 0.05 mV/sec, above which the polarization resistance curves became scan-rate dependent and did not represent necessary steady-state conditions. The

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software automatically calculated the polarization resistance from the slope at the origin of the polarization resistance curve. Finally, the corrosion rate was calculated from using Faraday's Law.

Corrosion rates generated from collected data varied considerably between replicates; however, averages of the data points between replicates appear to be representative of observed trends and the variation decreased after approximately 50 days of incubation. Also variation was considerably less in abiotic control cells. Pairs of bacterial types may have somewhat higher early corrosion rates, but with time decrease to near the same levels as the tests with single bacterial types. Still, the combination of all three types of bacteria shows significantly higher corrosion rates than any of the rest, especially up to about 20 days, where they reach a maximum, and then drop to lower values approaching corrosion rates for sulfate-reducing bacteria alone. Tests using combinations of bacterial types are continuing, but data were only available for 65 days at the end of the reporting period.

While it took several weeks to sufficiently establish conditions to measure significant corrosion rate changes using this described system, it appears that the iron oxidizers had the least effect on enhancing the corrosion of carbon steel, followed by slime-producing bacteria. The sulfate reducers appear to have the greatest ability to corrode carbon steel. Clearly, from these results it is evident that given a complete microbial community including all three of these classes of organisms, corrosion could proceed up to five times the rate observed in their absence, given the required conditions for microbial growth and activity. The system, as used, does have some limitations: the observed decrease in corrosion rates probably results from the depletion of oxygen within the system, which may not be representative of in situ repository conditions. Within the window of time between establishment of conditions and the observed decrease in corrosion rates, however, the system appears useful to determine corrosion rates of candidate barrier materials.

Corrosion rates were increased from approximately 25 $\mu\text{m}/\text{yr}$ (abiotic control) to 38 $\mu\text{m}/\text{yr}$, 50 $\mu\text{m}/\text{yr}$, and 75 $\mu\text{m}/\text{yr}$ in cell environments containing iron oxidizers, slime producers, and sulfate reducers alone, respectively. Corrosion rates increased even more when bacteria were paired together in various combinations. In a mixture of all three bacterial classes, corrosion rates reached a maximum at 125 $\mu\text{m}/\text{yr}$ and decreased thereafter, probably because of oxygen depletion in the sealed electrochemical measurement cells.

These results support a microbial corrosion mechanism in which anaerobic sulfate reducers grow most efficiently and corrosion is exacerbated under exopolymer films and insoluble iron hydroxide $[\text{Fe}(\text{OH})_3]$ deposits; a reduction of dissolved oxygen is also required on surrounding oxide and sulfide surfaces.

Greater details on the microbiologically influenced corrosion work and the processes used to isolate and propagate the various strains of microbes are given in the revised draft of the Engineered Materials Characterization Report (McCrigh, in prep.).

Forecast: Corrosion rate determinations will be carried out on mild steel coupons as just described at temperatures elevated to 50°C. In addition, individual Yucca Mountain strains of bacteria culled from various screening and assay results will be used in various combinations to assess the resistance of more corrosion-resistant alloys (e.g., nickel containing alloys, such as Alloy 400/ASTM B 127 and Alloy 825/ASTM B 424 N08825). The results will be compared with corrosion tests run under sterile conditions and those using whole Yucca Mountain-derived microbial communities. Testing of the more corrosion-resistant metal alloys, such as nickel-base and titanium-base alloys, necessitate a more sensitive detection of corrosion rates (because corrosion is expected to progress at a slower rate). Thus, improved inoculation protocols are devised, whereby bacteria are directly inoculated onto alloy coupons before insertion in the test cell, to decrease observed variations between otherwise like replicates and to improve the signal-to-noise ratio of compiled data. Also, various concentrations of artificial pore water have been tested with different amendments to the basic R2 media (i.e., added glucose and peptone) to improve the conductance of the media and accelerate rates of different corrosive microbial activities. Initial corrosion monitoring of stainless steel alloys will be undertaken at room temperature and subsequent tests will be conducted at elevated temperatures. Finally, corrosion activities will be screened and assayed under differing environmental conditions to continue to assess bounding conditions for microbially induced corrosion and to help determine the rates of these activities under simulated repository conditions.

Electrochemical Corrosion Studies

The purpose of this study is to evaluate the susceptibilities of candidate waste package container materials to localized corrosion, such as pitting and crevice corrosion, in a range of localized environments possible in the potential repository. Pitting is one of the most destructive and insidious forms of corrosion and requires an extended initiation period before visible pits appear. Pitting is an autocatalytic process, because the corrosion processes within a pit produce conditions that are both stimulating and necessary for the continuing activity of the pit. Crevice corrosion is usually associated with a small volume of stagnant solution caused by holes, gasket surfaces, and lap joints. This type of damage is believed to be the result of differences in metal ion or oxygen concentration between the crevice and its surroundings. This study focuses on determining critical potentials for the onset of pitting corrosion and crevice corrosion.

As reported in Progress Report #14 (DOE, 1996b), electrochemical testing of the nickel-base and titanium-base corrosion resistant alloys is continuing. With respect to the localized corrosion behavior of iron-nickel-chromium-molybdenum alloys, Alloys 825, G-3, and G-30 suffered from pitting corrosion in acidic brines at all three chloride levels tested, with Alloy G-30 showing the least attack. Transition from passivity to pitting conditions may be explained by a competitive adsorption mechanism by which chloride ions (Cl^-) move into the double layer (oxide/liquid interface), eventually reaching a critical potential, E_{pit} , corresponding to the Cl^- required to displace the adsorbed oxygen species. E_{pit} , as a function of chloride concentration for all three alloys, shifted to more negative (or active) values with increasing chloride concentration. This observation is consistent with the results obtained by Sridhar and Cragnolino (1993). In the presence of chloride, pitting of susceptible metals and alloys is due to the breakdown of protective oxide film. The value of E_{pit} for these three susceptible materials in

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solutions containing 10 wt % NaCl, shifted significantly to more noble values with a change in pH from acidic to neutral, as expected. The more active E_{pit} value in acidic solution results from the acceleration of the galvanic reaction caused by the high concentration of hydrogen (H^+) ions. At alkaline pH, Alloys G-3 and G-30 showed slightly lower E_{pit} values compared with those in neutral solution. However, E_{pit} for Alloy 825 was shifted to a more noble value at alkaline pH. That E_{pit} was shifted to more positive values in alkaline brines (compared with that in acidic solutions) is in line with the well-established pitting inhibition effect of hydroxyl ions. No explanation, however, can be provided as to the cause of lower E_{pit} value for Alloy 825 at the neutral pH. As to the effect of Cl^- concentration and pH on E_{prot} , the potential below which established pits will not grow, no consistent pattern was observed.

The overall results from the cycle potentiodynamic polarization tests indicate that of all the materials tested, Alloys C-4 and C-22, and titanium Gr-12 exhibited the maximum corrosion resistance, showing no pitting or general corrosion in any environments tested. These three highly corrosion-resistant materials maintained their shiny surface appearances even after exposure to the test solutions.

An effort was also made to correlate the corrosion potential E_{corr} to the test temperature and the solution pH. However, no consistent pattern was observed. The lack of a consistent pattern with temperature variations also has been shown in similar studies conducted by other investigators. More details on the electrochemical work can be found in the revised draft Engineered Materials Characterization Report (McCright, in prep.).

Work is in progress to determine the effect of the potential scan rate on the pitting and repassivation or protection potentials. This provides an important link between the potentiodynamic work and the potentiostatic work that will be emphasized in the future.

Forecast: Cyclic polarization studies are ongoing to evaluate the effects of Cl^- concentration, pH, temperature, and potential scan rate on E_{pit} and E_{prot} for materials susceptible to pitting corrosion. The determination of the potential scan rate effect forms and extrapolating the scan rate to zero provides the linkage between the potentiodynamic and potentiostatic methods. The effect of ferric ion will then be investigated, because ferric ion will be produced by the corroding steel outer barrier material. Ferric ion, particularly in acidic solutions, is well known as favoring pitting corrosion on some of the nickel-base alloys that are candidate materials for the inner barrier.

Galvanic Corrosion Studies

The objective of these studies is to provide an understanding of the electrochemical interaction between the dissimilar metals proposed for multibarrier waste package designs. The corrosion allowance outer barrier is expected to provide galvanic protection to the inner barrier. A first objective is to evaluate the effectiveness of this protection. A second objective is to determine if this protection will function in all circumstances. Even though the thicker outer corrosion-allowance barrier, under the current all-metallic multibarrier waste package design concepts, may provide corrosion protection to the inner corrosion-resistant barrier, galvanic

corrosion resulting from the breaching of the outer container may impact the performance of the inner container. Therefore, the galvanic corrosion behavior of inner and outer container materials must be evaluated to predict their service lives. Galvanic corrosion can be defined as accelerated corrosion of a metal because of an electrical contact with a more noble metal while exposed to a common electrolyte.

Specimens for galvanic corrosion tests using electrochemical methods were acquired, but tests have not yet begun.

Forecast: Work is planned in FY 1997 to evaluate the potentials of coupled corrosion allowance and corrosion resistant materials and the magnitude and direction of the current flowing between the coupled materials. The values of these electrochemical parameters will suggest the efficiency of galvanic effects. These tests will be run over a range of temperature, pH, and electrolyte composition. Different area ratios between the cathodic material and anodic material will be used. These electrochemical tests will provide a basis for interpretation of the longer term galvanic tests.

6.9.7 Performance Assessment Activity 1.4.3.1 - Models for Copper and Copper Alloy Degradation

Current designs, as described in the Controlled Design Assumptions Document (CRWMS M&O, 1996e), focus entirely on multibarrier waste package container configurations; therefore, modeling activities are reported under Performance Assessment Activity 1.4.3.3 in Section 6.9.9 of this progress report.

No progress was made during this reporting period for the modeling of various degradation processes of copper and copper-alloy materials; these were unfunded activities.

Forecast: See the forecast for Performance Assessment Activity 1.4.3.3 in Section 6.9.9 of this progress report.

6.9.8 Performance Assessment Activity 1.4.3.2 - Models for Austenitic Material Degradation

Current designs, as described in the Controlled Design Assumptions Document, focus entirely on multibarrier waste package container configurations; therefore, modeling activities are reported under Performance Assessment Activity 1.4.3.3 in Section 6.9.9 of this progress report.

No progress was made during this reporting period on this activity and the eight subactivities for modeling of various degradation processes of austenitic materials; these were unfunded activities.

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Forecast: See the forecast for Performance Assessment Activity 1.4.3.3 in Section 6.9.9 of this progress report.

6.9.9 Performance Assessment Activity 1.4.3.3 - Models for Degradation of Ceramic-Metal, Bimetallic/Single Metal, and Coatings and Filler Alternative Systems

The modeling work discussed below applies to the bimetallic/single metal design alternative, as discussed in the beginning of Section 6.9 of this progress report.

Subactivity 1.4.3.3.1 - Models for ceramic-metal systems. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.4.3.3.2 - Models for degradation of bimetallic/single metal systems.

Pitting Corrosion Model

The objective of the activity is to derive predictive tools that will enable using experimental data and analyses to assess the long-term performance of candidate materials under Yucca Mountain conditions. This work will ultimately describe the performance of the multibarrier waste package container, but as a first step, the modeling work has focused on the pitting corrosion of corrosion-resistant materials, such as one of the nickel-base or titanium-base alloys. Recently, limited effort has also begun on modeling the degradation of corrosion-allowance materials (for example, carbon steel) by dry oxidation or general atmospheric corrosion.

The probabilistic model PIGS (Pitting Initiation and Growth Stochastics), developed for pitting corrosion of corrosion-resistant materials, is described in the revised draft Engineered Materials Characterization Report (McCright, in prep.) and also in a separate report (Henshall, in prep.). This phenomenological, stochastic model can simulate the time evolution of the distribution in pit depths on a metal surface exposed to an aggressive environment. A review of the initial model revealed it to be capable of realistically simulating stochastic pit initiation. This model also includes simple phenomenological relationships describing the environmental dependence of the stochastic parameters. Therefore, it can simulate pit initiation and growth under variable-environment histories such as those expected in the repository.

Recent improvements to this model have focused on pit growth and the time evolution of the pit depth distribution. These improvements include the capability to model permanent pit growth cessation, methods to deterministically predict a nonlinear increase in maximum pit depth with increasing exposure time (for constant environmental conditions), and a more physically realistic treatment of stochastic pit growth. These improvements have resulted in predictions that are qualitatively more consistent with a variety of experimental data in the literature, for example the development of pit depth distributions with a positive skew and a long tail at large pit depths. Further, this model has been shown to be consistent with extreme-value statistical methods for predicting the logarithmic increase of maximum pit depth with increasing exposed surface area.

A critical need has been identified for generating experimental data for candidate container materials exposed to repository-relevant environments. These data are required to quantitatively assess and further develop the model. Preliminary pit depth distribution data for Alloy 825 (ASTM B 424 N08825) have been presented and were discussed in Progress Report #14 (DOE, 1996b). These data are qualitatively consistent with stochastic model predictions of a peak in the pit depth distribution at intermediate depths and show that this alloy is susceptible to pitting under aggressive conditions.

Forecast: The plans for the next year include augmenting of the electrochemical testing effort to produce pitting corrosion data that can be used directly in the model. Experiments will be performed, as they were in the initial work on Alloy 825, over the appropriate ranges of pH, chloride ion concentration, temperature, and applied potential for some of the other candidate materials. Again, the pit dimensions and distributions will be measured. The pitting corrosion model has been viewed as a prototype for other corrosion phenomena that also show probabilistic features, such as crevice corrosion, stress corrosion cracking, and microbiologically influenced corrosion.

Low-Temperature Oxidation Model

Work began on a deterministic model to predict long-term effects of low-temperature oxidation. The material of focus was carbon steel, the principal candidate for the outer barrier container material. Eventually, this work will be joined with a companion model on general aqueous corrosion. The transition between dry oxidation and wet corrosion will be determined by the experimental work identifying the critical relative humidity for the onset of aqueous effects on the metal surface. The experimental work is discussed in Section 6.9.6 of this progress report.

The low temperature oxidation model is discussed in the revised draft Engineered Materials Characterization Report (McCright, in prep.). Physically based model calculations indicate that dry oxidation is not expected to significantly degrade the performance of thick, corrosion allowance materials for hundreds to thousands of years.

Forecast: Further studies are in progress to consider internal oxidation (particularly important for the alloy steels) and the effect of water vapor in the atmosphere. The transition from dry oxidation to wet corrosion is an important boundary for this model. Once aqueous conditions are established on the carbon steel surface, the degradation rate becomes higher and the pH and several other chemical parameters become influential in determining the degradation rate. A deterministic model is planned for general aqueous corrosion.

6.9.10 Performance Assessment Activity 1.4.4.1 - Estimate of the Rates and Mechanisms of Container Degradation in the Repository Environment for Anticipated and Unanticipated Processes and Events, and Calculation of Container Failure Rate as a Function of Time

This activity includes Subactivities 1.4.4.1.1 (deterministic calculations) and 1.4.4.1.2 (probabilistic calculations). The objective of Subactivity 1.4.4.1.1 is to use the deterministic waste package system model developed in Activity 1.5.3.5 (Section 6.10.8 of this progress report), the scenarios developed in Activity 1.5.3.1 (Section 6.10.4 of this progress report), to estimate (a) the container degradation rates and (b) the time to initiation of radionuclide release from the waste. Because of heterogeneities in both the environment and components of the waste package design, the deterministic calculation of performance alone will not be sufficient to provide the performance measures for SCP Issue 1.4 for the set of waste packages and to support the reasonable assurance standard required by the NRC. Consequently, the objective of Subactivity 1.4.4.1.2 provides a probabilistic analysis of waste package container performance addressing these uncertainties, using uncertainty modeling methodologies developed in Activity 1.5.3.5 (Section 6.10.8 of this progress report).

Work on SCP Subactivities 1.4.4.1.1 (deterministic calculations) and 1.4.4.1.2 (probabilistic calculations) is described together because the calculations performed include both deterministic and probabilistic aspects.

The pitting corrosion model in YMIM (see Section 6.10.8 of this progress report) was expanded to consider the possibility of cessation of pit advance as a pit becomes larger. Presently, this possibility is indicated by limited data. The benefit of confirming this phenomenon was examined by a sensitivity study, calculating the container wall thickness needed as a function of the pitting cessation versus pit depth relationship.

The possibility that pits may cease to grow suggests that the upper tail of the pit depth distribution may begin to grow very slowly and eventually cease growing. The probability distribution over the depth of the deepest pits then becomes fixed. For any given wall thickness, only a fraction of the containers would be penetrated by pitting. Thus, it may be practical to specify a wall thickness for corrosion resistant materials such that only a small fraction of the containers will ever be penetrated by pitting.

This model was tested using published data for pitting in aluminum because data relevant to proposed materials was not yet available. Using these data, the model was calibrated to determine a distribution over pit growth rates and a rate of pit growth cessation. The calibrated model was used to compute a wall thickness such that only a small fraction of containers (e.g., 1 percent or 3 percent) would be penetrated by pits. For the unpenetrated containers, the pits simply cease to grow before penetrating the sample. For the data used in this analysis, the required thickness is not large (in the order of millimeters for aluminum under the conditions reported). This suggests that it may be practical to design containers such that only a small fraction will be penetrated by pitting over the life of the repository. However, these analyses must be revisited after data with relevant materials (Alloy 625) are available.

Forecast: See the forecasts for Sections 6.10.8 and 6.10.10 of this progress report.

6.9.11 Performance Assessment Activity 1.4.5.1 - Determination of Whether the Substantially Complete Containment Requirement is Satisfied

The objective of this activity is to use waste package modeling results from Activities 1.4.4.1, 1.5.4.1, and 1.5.4.2 (Sections 6.9.10, 6.10.9, and 6.10.10 of this progress report) to predict waste package containment performance using the scenarios and models developed in Activities 1.5.3.1 through 1.5.3.5 (Sections 6.10.4 through 6.10.8 of this progress report). The results of these calculations will then be compared with the interpretation of substantially complete containment to determine whether the performance objective has been met for all times during the containment period.

No progress was made during the reporting period; this was an unfunded activity.

See Section 6.9.10 of this progress report for details of the stochastic waste package degradation simulation model and the sensitivity study results using the model.

Forecast: Some information bearing on substantially complete containment will arise from activities discussed in Sections 6.10.8 and 6.10.10 of this progress report, although the near-term emphasis of those activities will be on release-rate modeling to support the total system performance assessment for the viability assessment.

6.10 ENGINEERED BARRIER SYSTEM RELEASE RATES (SCP SECTION 8.3.5.10)

SCP Section 8.3.5.10 addresses Issue 1.5, which asks whether the waste package and repository engineered barrier systems will meet the performance objective for radionuclide release rates as required by 10 CFR 60.113.

6.10.1 Performance Assessment Activity 1.5.1.1 - Integrate Waste Form Data and Waste Package Design Data

The objective of this activity is to accumulate the waste form data and waste package design data from waste producers, fuel manufacturers, and other repository studies. No tests or analyses are performed in this activity.

Subactivity 1.5.1.1.1 - Integrate spent nuclear fuel information. The spent nuclear fuel waste form testing data and modeling needs are being addressed in support of the Controlled Design Assumptions Document (CRWMS M&O, 1996e). Activity plans for oxidation tests, dissolution/release tests, and modeling dissolution/release are being revised. The information on spent nuclear fuel release modeling was incorporated in Section 3.5 of the Waste Form

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Characteristics Report, version 1.1 (Stout et al., 1996). Progress during this reporting period is presented in Sections 6.10.2 and 6.10.6 of this progress report.

Subactivity 1.5.1.1.2 - Integrate glass waste form information. The glass waste form testing data and modeling needs are being addressed in support of the Controlled Design Assumptions Document. Information was incorporated in Section 3.5 of the Waste Form Characteristics Report, version 1.1 (Stout et al., 1996). Progress during this reporting period is presented in Sections 6.10.3 and 6.10.7 of this progress report.

Subactivity 1.5.1.1.3 - Integrate waste package and repository design information. No progress was made during the reporting period; this was an unfunded activity.

Forecast: The Waste Form Characteristics Report will be updated for the spent nuclear fuel and glass waste forms. This report is being revised section by section, rather than waiting to revise the entire document.

6.10.2 Performance Assessment Activity 1.5.2.1 - Characterization of the Spent Nuclear Fuel Waste Form

The objective of this activity is to conduct tests that will provide data on the release rate of radionuclides from the spent nuclear fuel waste form.

Subactivity 1.5.2.1.1 - Dissolution and leaching of spent nuclear fuel. The objective of this subactivity is to generate spent nuclear fuel dissolution data for use in performance assessments and for direct use in licensing. As part of this task, saturated flow-through tests on spent nuclear fuel and uranium oxides are designed to measure dissolution rates of these materials and their dependence on several parameters such as solution pH, temperature, oxygen fugacity, flow rate, and solution anions, particularly carbonate species. The unirradiated uranium oxides represent new or zero burnup fuel. In addition, unsaturated drip tests are used to determine the rate of fuel alteration and release rates of different radionuclides under conditions of low-water-volume contact rates. Colloidal actinide species may form under these unsaturated conditions and be a major transport mode for radionuclides.

In the spent nuclear fuel flow-through tests, effort was focused in four different areas: (1) uranium oxide (UO₂) matrix dissolution rate tests on pressurized water reactor and boiling water reactors fuels at a variety of burnups; (2) dissolution rate tests with oxidized fuels; (3) grain-boundary penetration rate tests; and (4) gap inventory tests for iodine-129.

Cesium and strontium dissolved congruently with uranium, which is consistent with data obtained with grain specimens of the types of fuel tested so far. The technetium-99 data, however, have not been consistent for the different fuel specimens. A consistent explanation for why technetium-99 dissolves more slowly than the matrix in some, but not all instances, has not been formulated.

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At atmospheric oxygen and a nominal pH of 8, fuels with burnups ranging from zero (unirradiated UO_2) to 50 MWd/kgM (ATM-106) dissolved at approximately the same rate for a given test condition. The biggest difference is between the measured dissolution rate at 75°C in 2×10^{-2} molar carbonate solution for ATM-105 (7.8 mg/(m²•day)), compared with the measured value for UO_2 of 54 mg/(m²•day) and the value of 31 mg/(m²•day) for ATM-103, calculated from data-based models.

The intrinsic dissolution rates of ATM-104 and ATM-105 (data obtained using grain specimens) were not significantly affected by oxidation but there was a modest increase in the intrinsic dissolution rate of ATM-106 fuel grains. Secondly, oxidation left the dissolution rate of ATM-105 particles unchanged, which implies that the depth of water penetration into the grain boundaries was unchanged by the oxidation.

The data from all three particle specimens studied (unoxidized ATM-104 and ATM-103 plus oxidized ATM-104) suggest that the entire grain boundary inventory of cesium was dissolved during these tests. This indicates that water must have penetrated throughout the entire grain boundary volume of the particles (700 to 1700 μm). This interpretation of the cesium data conflicts with conventional expectations, but the uranium data also acquired are not inconsistent with this idea.

In the unsaturated tests, two commercial spent nuclear fuels, ATM-103 and ATM-106, are being tested in three types of tests: high drip rate tests, low drip rate tests, and vapor tests. A surrogate water, EJ-13, was produced by reacting water from ground-water well UE-25 J#13 with Yucca Mountain Tuff for approximately 80 days at 90°C. The fuel in the tests has undergone 48 months of reaction at 90°C by the end of September. A shipment of approved test materials was sent from Pacific Northwest National Laboratory (Richland, Washington) to Argonne National Laboratory (Argonne, Illinois) for additional samples to extend the range of these tests.

Release from the unsaturated tests at the 1.6-year test interval was compared with that at 2.5 and 3.1 years to minimize the effect of radionuclide release from the fuel gap and to determine if radionuclide release changed as a function of reaction time. For the high drip rate tests, the technetium-99 release rates at all test intervals were comparable to those measured in flow tests in which the amount of water for transport was maximized. The cesium-137 interval release fractions remained an order of magnitude smaller than the technetium-99 release rate. This reduced rate was attributed to the incorporation of cesium into alteration products. The uranium-238 interval release fractions, as well as those of the transuranics, decreased drastically after the 1.6-year sampling interval. This behavior suggests that most of the actinides were incorporated into alteration and precipitation products that were retained on the spent nuclear fuel surface.

The effect of varying amounts of water on radionuclide release was also examined. The high drip rate tests appeared to have sufficient liquid to transport dissolved material from the spent nuclear fuel to the test vessel. For the low drip rate and the vapor tests, water evaporation was an important parameter. For both, film transport was important for radionuclide release. In the vapor tests, the increasing release of technetium-99 as a function of time suggests that the

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formation of a thin water film on the fuel can transport material under the unsaturated conditions of these tests.

Because direct unsaturated testing of spent nuclear fuel is difficult because it is highly radioactive, unirradiated UO_2 is also being used as a surrogate for spent nuclear fuel. Uranium release from the UO_2 samples was very rapid between one and two years of testing, followed by relatively low rates of release over the two- to ten-year period. The initial rapid release could be correlated with an episode of uraninite grain boundary corrosion and spallation of micrometer- to submicrometer-sized UO_2 particles from the sample surfaces. Subsequent to this period, the development of a dense mat of alteration and precipitate phases resulted in reduced particulate spallation and lower uranium release rates. Unfiltered uranium release rates from the latter period were generally between 0.1 and 0.3 $\text{mg}/(\text{m}^2 \cdot \text{day})$, based on nominal areas of the original sample.

Most of the uranium released from the samples was recovered in a solidified form, either as fine particulate matter or as insoluble components that had precipitated out of solution when it came in contact with the surface of the stainless steel test vessel. Less than 2 percent of the uranium was released in a soluble fraction that passed through a 5 nm filter.

The sample reaction trends observed in these unsaturated UO_2 tests have closely replicated those that occur in natural geologic systems, such as the Nopal I deposit in Mexico (Bates et al., 1995). Both the natural and experimental systems display a paragenetic sequence of mineral phases that is characterized by the following trend: uraninite (UO_{2+x}) $\Rightarrow$ uranyl-oxide hydrates (including schoepite-type and alkali + alkaline earth uranyl-oxide hydrates) $\Rightarrow$ uranyl silicates $\Rightarrow$ alkali + alkaline earth uranyl silicates. This similarity indicates that the UO_2 in the experiments has reacted by the same mechanism as uraninite in the natural deposits. Thus, both the present tests and the natural analog reactions may be used to simulate the reaction progress expected for uranium at the potential Yucca Mountain repository. Alkali and alkaline earth uranyl silicates represent the long-term solubility-limiting phases for uranyl ions in the UO_2 tests, natural analog occurrences, and possibly for spent nuclear fuel at the potential Yucca Mountain repository.

Forecast: Flow-through dissolution measurements on spent nuclear fuel will continue. There are still major gaps in the data base of flow-through tests for fuels with different burnups, most notably as follows: (a) the remaining three extreme conditions should be tested for the highest burnup fuel currently available for testing, ATM-106; (b) there are no data for low burnup fuels between zero (UO_2) and 30 MWd/kgM (ATM-103) (fuel specimens with burnups of about 15 to 20 MWd/kgM are available for testing from the ends of fuel rods on hand, and the current test plan calls for testing these fuels in the near future); and (c) fuels with burnups up to about 70 MWd/kgM should be tested but none are currently available.

The unsaturated tests will continue. Detailed analysis of the leachates from the spent nuclear fuel tests will continue in the next year to determine if there is a decrease in the leach rate and a change in the composition, form, and quantity of the radionuclides. The alteration products on the spent nuclear fuel will continue to be identified. Attention will be paid to the type and

depth of reaction within a spent nuclear fuel fragment. A detailed test plan, which was written this year, will be implemented to address issues identified during the ongoing testing of spent nuclear fuel. The reacted UO_2 samples from the unsaturated tests will be cross-sectioned so that a three-dimensional representation of the sample reactions and a more quantitative determination of crystal phase compositions can be obtained.

Subactivity 1.5.2.1.2 - Oxidation of spent nuclear fuel. The oxidation of spent nuclear fuel under potential repository conditions depends primarily on temperature and time after the spent nuclear fuel is exposed to atmospheric oxygen. Spent nuclear fuel oxidation is a degradation or alteration mode that can significantly increase the potential radionuclide release rate in the potential repository. This results from the transformation of the UO_2 phase of spent nuclear fuel to a U_4O_9 lattice (slight volume decrease) and then to U_3O_8 (about a 30 percent volume expansion), increasing the surface area of the spent nuclear fuel exposed relative to the original pellet fragment/grain area. The U_3O_8 phase can split the zircaloy cladding lengthwise. Dry-bath weight gain tests are in progress to determine spent nuclear fuel oxidation response. These are long-term weight gain tests conducted in a hot cell. These tests primarily use low temperatures (less than 200°C) to examine oxidation rate, but one dry bath operates at 255°C to accelerate the oxidation rate. On the basis of information obtained from the dry-bath tests, thermogravimetric apparatus tests were initiated at a higher range of temperatures (250° to 320°C). These two types of tests will provide temperature-time-phase response as UO_2 spent nuclear fuel oxidizes to U_4O_{9+x} , then to U_3O_{8+x} , and finally to UO_3 .

The dry-bath oxidation testing continued at a reduced level. The low temperature (less than 200°C) oxidation test continued to show no definitive trends to initiate a U_3O_8 phase transition. These results are expected and are consistent with current model extrapolations. The 255°C dry-bath tests are showing oxygen weight gains above the $\text{UO}_{2.4}$ plateau levels and have variability in oxygen weight gain rates. Microscopic examination by x-ray powder diffractometry of samples from the 255°C temperature dry bath have detected only minor U_3O_8 lattice formation, even though the oxygen to metal weight gain has changed from $\text{UO}_{2.4}$ to $\text{UO}_{2.6}$ in some samples. The use of other microscopic methods to analyze these samples indicated that an amorphous phase transition from the $\text{UO}_{2.4}$ to a U_3O_8 phase may be occurring. The intermediate step of a nanocrystalline U_3O_8 material is consistent with limited transmission electron microscopy examinations and estimated weight gain measurements. Nanocrystalline-sized material particles would not necessarily provide distinct x-ray diffractometry data to identify lattice structures.

The thermogravimetric apparatus tests will continue to show significant variability in the oxidation response in going from the U_4O_{9+x} ($\text{UO}_{2.4}$) state up to the U_3O_8 state for a subset of test specimens taken from ATM-105. The mechanistic causes of this variability are not currently understood. One hypothesis is that a spatial variation in chemical composition exists at the rim of a pellet because of a higher burnup phenomenon at the outer radius. Recent thermogravimetric apparatus tests on carefully selected subsets of samples have been performed. The samples are selected by breaking apart one large pellet fragment into smaller fragments (~200 mg sized). Selecting samples this way provided some control over the spatial position of the small fragments and reduced the variations in thermogravimetric apparatus test data. These data are

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consistent with the hypothesis that the large variation in thermogravimetric apparatus test data is a result of chemical compositional variations due to rim effects at the outer radius of pellets. Additional thermogravimetric apparatus tests are being performed to substantiate this hypothesis. Results of these tests will be used to develop and refine a bounding oxidation rate model for the U_3O_8 phase transformation.

Forecast: Dry-bath testing will continue and the tests will be monitored, but limited analytical work, and little or no spent nuclear fuel sampling or oxidation analysis, will be performed. Thermogravimetric apparatus oxidation testing will continue and include generating time-temperature curves that describe the onset of spent nuclear fuel oxidation of the U_3O_8 state. These curves will be generated as a function of burnup and fuel type to study the variability in oxidation response.

Subactivities 1.5.2.1.3 through 1.5.2.1.6. No progress was made during this reporting period on the four subactivities that address (1) the corrosion of zircaloy, (2) the corrosion of and radionuclide release from other materials, (3) the evaluation of the inventory and release of carbon-14 from the zircaloy cladding, and (4) other experiments on the spent nuclear fuel waste form.

6.10.3 Performance Assessment Activity 1.5.2.2 - Characterization of the Glass Waste Form

The objective of this activity is to provide the data required to calculate radionuclide release rates from glass waste forms.

Subactivity 1.5.2.2.1 - Leach testing of glass. These tests provide data on radionuclide release mechanisms and the rates of degradation or alteration for glass waste forms. The data are being used to constrain and guide ongoing model development for glass corrosion. Additional testing will be required to model degradation or alteration modes for glass waste forms, as well as the subsequent dissolution and release of radionuclides as soluble and colloidal species over the range of potential repository environments. This information is provided directly to repository performance assessment models, such as YMIM (Gansemer and Lamont, 1995), for use in evaluating the total release of radionuclides from the glass waste form.

Long-term unsaturated tests (drip tests) of two glass compositions (Savannah River Defense Waste Processing Facility and West Valley ATM-10) continue in two test series labeled the N2 and N3 series. These tests are being used to determine the types and quantities of radionuclide elements released from waste glasses when subjected to an intermittent dripping water contact scenario. Both soluble and colloidal radionuclide releases of actinides and technetium are being measured. A 304L stainless steel sample holder is also present in these tests to simulate the presence of the pour canister material on glass waste form behavior.

The Defense Waste Processing Facility glass is being tested in the N2 test series that has been in progress for 552 weeks (10.6 years) as of September 30, 1996. The tests were sampled

on June 18, 1996 as scheduled using the newly revised unsaturated test procedure. The revised procedure includes videotaping of the sample assembly during withdrawal to help interpret the analytical results and to qualitatively describe the reaction progress. The N2#10 sample again showed more extensive spallation of the alteration layer. Also, because of increased amounts of colloidal material in solution, gamma spectroscopy (which is insensitive to self-shielding) is being substituted for alpha spectroscopy for transuranic analyses.

The West Valley glass (ATM-10) is being tested in the N3 test series, which has been in progress for 477 weeks (9.2 years) as of September 30, 1996. The tests were successfully sampled as scheduled on July 15, 1996. As with the N2 series, solution samples were taken following the newly revised unsaturated test procedure. For both of the N2 and N3 samples, transuranic entrainment by colloids and particulates will be determined by ultracentrifugation-filtration of the test solutions, which removes materials with dimensions greater than about 0.1 micron. Inductively coupled plasma mass spectrometry analysis of cation concentrations in the solutions from both the N2 and N3 tests is in progress. No further analytical work on either of these sample sets will be performed.

These tests are providing data on radionuclide release mechanisms and degradation/alteration rates of glass waste forms. These data are being used to constrain and guide on going model development for glass corrosion. Additional glass waste form testing will be required to model glass degradation/alteration modes and the subsequent dissolution and release of radionuclides as soluble and colloidal species over the range of potential repository environments.

Subactivity 1.5.2.2.2 - Materials interactions affecting glass leaching. The N2 and N3 test series contain stainless steel holders that simulate the presence of the 304L pour canister that will be present in the repository. Colloidal-sized iron particles have been identified in the N2 and N3 test solutions. This is important because sorption of radionuclides onto these particles provides a transport mechanism for radionuclides that is not solubility controlled. No other work in this subactivity is in progress.

Forecast: Degradation/alteration testing of the glass waste form in these long-term unsaturated tests will continue. Limited analysis of colloids from previous tests will be performed. Ongoing long-term tests on additional glass compositions will be brought up to quality affecting level.

Subactivity 1.5.2.2.3 - Cooperative testing with waste producers. No progress was made during the reporting period; this was an unfunded activity.

Forecast: Degradation and alteration testing of the glass waste form in these long-term unsaturated tests will continue. Limited analysis of colloids from previous tests will continue.

6.10.4 Performance Assessment Activity 1.5.3.1 - Integrate Scenarios for Release From Waste Package

The objective of this activity is to first identify the features, events, and processes and then to develop the scenarios composed of these features, events, and processes for which the engineered barrier system subsystem must be analyzed in accordance with 10 CFR 60.113. This paragraph of 10 CFR Part 60 sets quantitative performance requirements to be satisfied by the waste package and engineered barrier system, assuming anticipated processes and events. Thus, this activity must identify which features, events, and processes and scenarios are expected.

Subactivities 1.5.3.1.1 through 1.5.3.1.4. No progress was made during this reporting period on the four subactivities that cover: (1) developing scenario identifications, (2) separating scenarios into anticipated and unanticipated categories, (3) developing parameters of the scenarios, and (4) comparing the anticipated scenarios with the design envelope of the waste package. Scenarios for waste package criticality are described and evaluated in Section 5.1.3 under Subactivity 1.10.2.3.3 in Section 5.1.3 of this progress report. Occurrence of these scenarios would change the source term for radionuclide release and could possibly alter the disposal container. Analyses reported in Sections 5.2.1 and 5.2.3 of this progress report will contribute to the technical basis for developing the scenarios for the next total system performance assessment. Submodel development in Section 6.10.8 of this progress report will use and possibly extend the scenarios work reported in Section 6.10.4 in Progress Report #13 (DOE, 1996j).

Forecast: See the forecast for Section 6.10.8 concerning scenarios as a guide to process model development. In future periods the features, events, processes, and scenarios will be identified for the engineered-system component of the total system performance assessment for the viability assessment.

6.10.5 Performance Assessment Activity 1.5.3.2 - Develop Geochemical Speciation and Reaction Model

The objective of this activity is to further develop the geochemical modeling code EQ3/6 for use in modeling waste form radionuclide release and the behavior of the released radionuclides.

Subactivity 1.5.3.2.1 - Develop data base for geochemical modeling. Major upgrades were completed to the hardware facilities and relational data base system used to develop and maintain the GEMBOCHS thermodynamic data base and software library. Specifically, the Sun SPARC-10 GEMBOCHS server was expanded from a two- to a four-disk configuration, the operating system was upgraded from SunOS 4.1.3 to Sun Solaris 2.4, the Ingres installation was upgraded from Ingres 6.4 to CA-OpenIngres 1.2, and the GUI (Graphical User Interface) development package was upgraded from Windows4GL 2.0 to CA-OpenROAD 3.0. The GEMBOCHS data base and associated application software were successfully ported to this new

environment. These hardware, operating-system, and Ingres upgrades significantly improved data base security and the run-time performance of all GEMBOCHS components.

GEMBOCHS was augmented by the inclusion of reference-state dissociation constants for approximately 300 rare-earth aqueous complexes and 150 solids (Spahiu and Bruno, 1995). Roughly half of these complexes overlap with those for which reference-state standard molal properties and equation-of-state parameters (Haas et al., 1995) have been incorporated into GEMBOCHS; hence, they provide a valuable source for comparison. The other half are new, expanding considerably the compositional range of problems that can be addressed using dependent geochemical modeling software. Moreover, approximately 90 percent of the solids for which dissociation constants are given by Spahiu and Bruno (1995) were previously unrepresented in GEMBOCHS; as a result, this new compilation fills a critical void in terms of rare-earth solid phases. Altogether, these new data permit improved modeling capabilities for both direct and analog geochemical scenarios relevant to the potential repository at Yucca Mountain. Numerous, relatively small-scale additions and revisions have also been incorporated into the data base and associated software. New thermodynamic datafile suites that incorporate all the foregoing improvements have been generated for use with both EQ3/6 and GWB (Bethke, 1994) and are available on the Internet via anonymous file transfer protocol (ftp) access.

Forecast: The GEMBOCHS data base and software library will continue to be improved by the inclusion of new and revised thermodynamic data and extrapolation algorithms as they become available in the scientific literature. These improvements will be incorporated into revised EQ3/6 and GWB datafile suites that will be available on the Internet via anonymous ftp access.

Subactivity 1.5.3.2.2 - Develop geochemical modeling code. The objective of this task is to further develop the geochemical modeling software EQ3/6 (Daveler and Wolery, 1992; Wolery, 1992; Wolery and Daveler, 1992), which provides capabilities for analyzing and simulating interactions among water, rock, nuclear waste, and other repository components in the near-field environment, the altered zone, and the far-field environment.

No progress was made during the reporting period; this was an unfunded activity. Qualified versions of the software are being maintained in the Version 7 line and additional modeling capabilities have previously been added to the Version 8 line.

Forecast: No activity is planned for FY 1997.

6.10.6 Performance Assessment Activity 1.5.3.3 - Generate Models for Release From Spent Nuclear Fuel

The objective of this activity is to develop models for the oxidation, degradation, dissolution, and radionuclide release rate response of spent nuclear fuel waste forms.

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Subactivity 1.5.3.3.1 - Generate release models for spent nuclear fuel. The primary transport mode of radionuclides from spent nuclear fuel waste forms is by water contacting, wetting, dissolving, and reacting at the surface of the spent nuclear fuel. The development of a model to describe the physical, chemical and radiolytic processes requires several submodeling steps. These include a submodel to predict the oxidation state of the fuel (UO_2 , U_4O_{9+x} , U_3O_8 or UO_3). Given the oxidation state, the transport equation, which is a mass balance equation, is the basis for developing the release submodels that depend on degradation and dissolution rates.

UO_2 spent nuclear fuels oxidize to higher uranium oxide phases in an oxygen atmosphere. The oxidation response of spent fuels affects the radionuclide release in potential repository environments because of two independent functional consequences of the higher oxides. The first effect is geometrical and results from the surface area and volume changes that occur as the higher oxides form. The second effect results from the higher dissolution rate of the U_3O_8 oxide and the UO_3 oxide hydrates. A model of UO_2 spent nuclear fuel oxidation is being developed.

The basis of spent fuel oxidation response model development depends strongly on experimental data obtained from thermogravimetric analysis and oven dry bath oxidation testing methods (see Sections 6.9.6 and 6.10.2 of this progress report). The models provide response functions for the elapsed time to higher oxidation phases as a function of temperature and nominal grain size, and for the quantity (volume) of a higher oxidation phase as a function of time, temperature, and nominal grain size. The two spent nuclear fuel oxidation phase responses examined thus far are the UO_2 to U_4O_9 phase transformation and the U_4O_9 to U_3O_8 phase transformation.

For dissolution response, nonequilibrium thermodynamics was used to develop functional relationships (Stout, 1996). Two different function forms were developed to describe the dissolution response of unoxidized UO_2 spent nuclear fuel waste forms. The first form is a classical Onsager relationship (deGroot and Mazur, 1962) for the dissolution rate, which is linearly related to the energy change of the solid dissolving into a liquid. This is expected to be descriptive of the dissolution response close to thermodynamic equilibrium. The second function form explored is a classical Butler-Volmer relationship (Bockris and Khan, 1993) for the dissolution rate, which is exponentially related to the energy change of the solid dissolving into a liquid. These function forms were used for regression analyses over subsets of unirradiated UO_2 and spent nuclear fuel UO_2 dissolution rate data. The function forms and the results of the regression analyses were incorporated in the recent revision of Section 3.4.2 of the Waste Form Characteristics Report, version 1.1 (Stout et al., 1996).

The Butler-Volmer type model describes some features of the chemical dissolution processes far from thermodynamic equilibrium and provides a reasonably good fit to the available data. The model is nonlinear, however, because the Butler-Volmer model's energy change term is in the exponent and contains quadratic terms. Depending on the terms and coefficients in the model, extrapolation outside the measured independent variable space could cause large prediction errors and should be used with caution.

Model development to describe the unsaturated test data continued. The unsaturated test data indicated that significant alteration of the fuel surface has occurred during the 3.5 years of testing, and the surfaces of grains are probably exposed and wetted by a thin water film. Using the high and low drip-rate test data, preliminary values for a length scale parameter are being determined.

Forecast: Development of submodels for release rate terms in the mass transport model will continue. Submodels will be refined that are consistent with the limited subsets of dissolution/release data. To include known effects of UO_2 spent nuclear fuel oxidation on release rates, models for fuel oxidation response will continue to be developed and refined.

6.10.7 Performance Assessment Activity 1.5.3.4 - Generate Models for Release From Glass Waste Forms

The objective of this activity is to develop models for radionuclide release from the glass waste form as a function of potential repository conditions.

Subactivity 1.5.3.4.1 - Generate release models for glass waste forms. Chemical modeling of glass degradation is being used to synthesize results from on-going experimental work, to determine the rate-limiting chemical mechanisms controlling glass alteration rates, and to provide a mechanistically based method for making long-term predictions of glass degradation.

Current work is focused on examining the effect of dissolved cations such as magnesium, iron, and aluminum on glass waste form performance, with most of the work concentrating on magnesium. Previous experimental data suggest that dissolved magnesium can significantly increase glass durability. Analysis of the available data and modeling results to date suggest that magnesium has no effect at dissolved concentrations below a threshold that roughly corresponds to the saturation level of sepiolite, an hydrous magnesium silicate phase. The implication is that above that level of magnesium concentration in solution, a reaction between magnesium and silica being dissolved from the glass causes the precipitation of sepiolite or a sepiolite-like phase on the glass surface that armors the glass from further reaction. The reduced rate at which the glass now dissolves is difficult to estimate because the control on the reaction rate is essentially physical (i.e., transport) rather than chemical. More experimental work is needed to confirm this hypothesis and better quantify the overall process.

Forecast: The analysis of the effect of magnesium on glass waste form durability will continue. In addition, the work on developing a better hydration theory model of glass composition-durability will continue. This work is based on the results of nuclear magnetic resonance studies of Savannah River Laboratory analog glasses that indicate boron-rich clustering in the glass. Better correlations of glass composition with glass durability will be possible if this clustering is taken into account.

6.10.8 Performance Assessment Activity 1.5.3.5 - Waste Package Performance Assessment Model Development

The objectives of this activity are to (a) integrate submodels of processes that affect radionuclide release from waste packages into a system model for waste package performance (Subactivity 1.5.3.5.1), (b) to develop a method for providing probability distributions for individual waste package and ensemble performance that incorporate uncertainties in conditions and waste package parameters (Subactivity 1.5.3.5.2), and (c) to determine experimentally what fraction of the water dripping onto a container would enter the container through a breach in the container wall (Subactivity 1.5.3.5.3).

Subactivity 1.5.3.5.1 - Development of system model

Engineered System Performance Assessment Model

Qualification of the engineered-system performance assessment model YMIM (Gansemer and Lamont, 1995) was suspended at a logical interim step that could allow work to be restarted if desired. The source code restructuring for object-oriented design was completed and a set of design-descriptive drawings for one module of the program was completed and reviewed internally. The idea is that a combination of narrative, diagrams, and tables can document the functional requirements and the code structure in a multi-viewed, easily reviewable form. A documented development record, as well as a documented final version, supports qualification. The restructured YMIM version, while partially on the path toward qualification, can be used as the basis for future rapid prototyping changes to study the working of new conceptual models as they are developed.

Conceptual model development progressed for container pitting corrosion and lifetime, geochemistry of water entering a breached waste package, and spent nuclear fuel cladding creep. The pitting and geochemistry models were added to YMIM to examine how they affect the container and waste form performance, respectively.

Pitting Model for Corrosion Resistant Materials

The pitting model for corrosion resistant materials has been extended to include (a) a probability distribution over intrinsic growth rates of pits, (b) changes in growth rates as a function of the depth of a pit, and (c) the probability that a pit may cease to grow. Effects of the pitting phenomena on container lifetime are discussed in Section 6.9.10 of this progress report.

Geochemistry of Water Entering the Containers

The geochemistry of water encountering a waste container depends on the introduced materials such as concrete and reactions with the iron in the container wall. The interactions between the water and the mild steel of the outer container were modeled, including the dissolution of iron from the container wall and the formation and deposition of reaction products on the surface of the steel. Water was assumed to move through the outer container in a channel

(such as a pit). Two cases were analyzed: (1) UE-25 J#13 water entering the drift with no significant introduced materials, and (2) UE-25 J#13 water entering the drift with substantial amounts of concrete present. In the first case, the pH of the water increases slightly from about 7 as it passes over the steel of the outer container. Carbonates are not changed significantly. In the second case, the pH of the water encountering the container is around 12, because of its reactions with the introduced concrete. However, in the initial years after the flow starts, the pH of the water is reduced to about 6 as it reacts with the iron in the steel of the outer container. After an initial phase, the reactions with the steel slow down and the pH of the water entering the container approaches 10.

The calculations indicate that the duration of this initial period of pH reduction depends strongly on the solubility of the iron of the outer container wall. For a range of iron solubility that might be expected in commercially produced steel, the duration of the initial period of pH reduction can range from about 100 years to many thousands of years. Effects of the water geochemistry on waste form dissolution are discussed in Section 6.10.9 of this progress report.

Cladding

Spent nuclear fuel cladding can provide an additional measure of protection to the spent nuclear fuel pellets, if the cladding performance can be determined or bounded. A significant mode of cladding failure is through creep at elevated temperatures. This performance has a strong interconnection with the thermal design of the waste emplacement. The creep measurements reported in the journal literature have a range of variation due apparently to different manufacturing and metallurgical treatments. Several extrapolation methods are used in this literature. The empirical fits and extrapolations of the data set are being reevaluated. The effects of creep-rate extrapolations on the predicted cladding performance have been evaluated.

The YMIM and AREST (Liebetrau et al., 1987; Engel and McGail, 1993; Buxbaum and Engel, 1991) computer codes for engineered barrier system performance are being compared. YMIM output formats were changed to make the comparison easier. The comparison is showing the uses of different levels of model approximation for different assessment tasks and is highlighting some points of alternative conceptual process models.

Stochastic Waste Package Degradation Model

The stochastic waste package degradation computer code WAPDEG (Waste Package Degradation) was developed (Atkins and Lee, 1996; Lee et al., 1996a) in a parallel effort with the YMIM and associated submodel development. Version 1.0 of WAPDEG computes the failure time of waste packages (defined as having at least one pit penetration) and the subsequent pitting degradation of the waste packages. The model builds on the pitting corrosion model for the Alloy 825 (ASTM B 424 N08825) inner barrier used for Total System Performance Assessment - 1993 (Andrews et al., 1994; Wilson et al., 1994), on the waste package degradation modeling approach of Total System Performance Assessment - 1995 (CRWMS M&O, 1995a), and on new corrosion models for the carbon steel outer barrier (Lee et al., 1996b). The most recent of these approaches, the Total System Performance Assessment - 1995 version of waste

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package degradation model, captures only a few corrosion degradation modes. The new waste package degradation model includes improvements in the existing corrosion models, additional important corrosion modes, and more realism in modeling the corrosion expected in the drift environments of the potential repository.

A concept of "patching" the waste package surface was developed to reflect more adequately the general corrosion data from the literature and the concept was implemented in the model. In this concept, the waste package container surface area is divided by the surface area for sample coupons used in corrosion tests. The portion of the waste package surface equivalent to the surface area of a single sample coupon is referred to as a "patch." A uniform general corrosion depth is assumed within a single patch and the uniform general corrosion depth is multiplied by (normally distributed) pitting factors to calculate pit depth distribution in the outer barrier (Lee et al., 1996b). This "patching" concept is useful to better model galvanic protection of the Alloy 825 inner barrier by the carbon steel outer barrier (i.e., ratio of exposed surface areas between two metals and/or thickness reduction of the outer barrier), effects of chemistry of water contacting the waste container, locally enhanced corrosion within a waste package due to localized dripping, salt-scale buildup, etc.

A corrosion time concept involving a modified time scale was developed to better represent the corrosion of the carbon steel outer barrier in dynamically changing exposure environments with time. In general, simulation results with the corrosion time concept predict earlier and a greater number of pit penetrations than using the real time. This is expected in light of the evolution of the exposure conditions (or near-field environments) into more corrosive (i.e., more humid) conditions with time. The effects of the evolving exposure conditions on the waste package performance (i.e., failure and pitting degradation) are better represented by using the corrosion time concept.

A series of waste package degradation simulations using the patching approach with the corrosion time concept was performed to study the sensitivity of waste package performance to the spalling of the corrosion products from the carbon steel outer barrier. Effects of different spalling thicknesses (from 1 to 10 mm) on the waste package performance were analyzed. The results demonstrate that spalling of the corrosion products from the carbon steel outer barrier significantly affects waste package performance. Better understanding (or definition) of the threshold spalling thickness would enhance the confidence in predicting the waste package performance.

A pitting model for the Alloy 825 inner barrier was developed in Total System Performance Assessment - 1995 from an expert elicitation on (time-independent) pit growth rate ranges for Alloy 825 (Andrews et al., 1994). For WAPDEG, two additional alternative inner barrier pitting corrosion models were developed from the same expert elicitation and the sensitivity of waste package degradation to the alternative pitting models was studied. The analyses demonstrate that the three alternative models for the inner barrier pitting corrosion have significant effects on the waste package performance (in terms of waste containment and radionuclide release). The analysis results suggest that the current inner barrier pitting model derived from an expert elicitation should be substantiated and/or improved to predict, with an

adequate level of confidence, the waste package performance in the potential repository exposure environments.

Subactivity 1.5.3.5.2 - Development of uncertainty methodology. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.5.3.5.3 - Water flow into and out of a breached container. No progress was made during the reporting period; this was an unfunded activity.

Forecast: Enhanced YMIM subsystem models will be developed for intended use in the total system performance assessment for the viability assessment. The analytic model of pit growth is available to assist in designing experiments to study pit growth phenomena. Container material performance modeling status and total system performance assessment for the viability assessment will be the subject of a workshop in the next reporting period.

Planned WAPDEG improvements include (a) incorporating a substantiated/improved inner barrier pitting model, (b) incorporating a substantiated/improved pitting model of the carbon steel outer barrier, (c) incorporating a substantiated/improved model for galvanic protection of the Alloy 625 (ASTM B 443) inner barrier by the carbon steel outer barrier, and (d) incorporating a model for dry oxidation of the outer barrier carbon steel. The model improvements will be based principally on corrosion testing and submodel development described in other sections of this progress report.

6.10.9 Performance Assessment Activity 1.5.4.1 - Deterministic Calculation of Releases from the Waste Package

The objective of this activity is to use the waste package system model developed in Performance Assessment Activity 1.5.3.5 (Section 6.10.8 of this progress report) to predict waste package performance using the scenarios developed in Performance Assessment Activity 1.5.3.1 (Section 6.10.4 of this progress report).

The implications of waste-package-level geochemistry calculations reported in Section 6.10.8 of this progress report were studied using the waste form dissolution equation in YMIM. The dissolution rate of the waste form at a pH of 10 was found to be about one third the dissolution rate at a pH of 6. Previous performance assessment analyses using YMIM have assumed pH values on the order of 6 to 7. These results indicate that when concrete is introduced into the drift the dissolution rate of the waste form may be substantially slowed, depending on the iron dissolution rate of the steel outer container. However, the dissolution rate of the steel is a critical parameter that might be expected to vary over a range that could substantially affect these conclusions.

Forecast: See Section 6.10.10 of this progress report.

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6.10.10 Performance Assessment Activity 1.5.4.2 - Probabilistic Calculation of Releases from the Waste Package

The objective of this activity is to provide a probabilistic analysis of waste package performance addressing uncertainties in the waste package environment and components and to provide the probability distribution of radionuclide release rates for use in SCP Issue 1.1 (Section 6.13 of this progress report), using the uncertainty model developed in Performance Assessment Activity 1.5.3.5 (Section 6.10.8 of this progress report). Probabilistic analyses are needed because deterministic calculations of performance alone may not be sufficient to provide the performance measure for the set of waste packages for SCP Issue 1.5 (Section 6.10 of this progress report) and to support the reasonable assurance required by the NRC.

No calculations in this category were performed. Effort during this reporting period was instead on a cycle of improvements to the models; see Section 6.10.8 of this progress report.

Forecast: Effects of drift-scale thermal-hydrological and thermal-chemical processes on the engineered barrier system performance will be evaluated on a scoping basis. Results will be used to guide subsystem model development and scenario development for the total system performance assessment for the viability assessment. The current state of model representation and needed refinements for the total system performance assessment for the viability assessment will be the subject of a multidisciplinary workshop in the first half of FY 1997.

6.10.11 Performance Assessment Activity 1.5.5.1 - Determine Radionuclide Transport Parameters

The objective of this activity is to measure the distribution of actinides and fission products in rock samples. The rock samples will be subjected to contact with radionuclides under a variety of conditions so that the effects of degree of saturation and transport scale can be evaluated.

Estimates to credibly bound the type, concentration, and nature of the radionuclides that might potentially escape the engineered barrier system/near-field environment (that is, the source term) are needed before the expected performance of a potential repository can be assessed. Estimating the source term will require a combination of experimental and modeling tasks designed to assess both the release of radionuclides from the waste form and their transport through and interaction with the components of the engineered barrier system and near-field environment.

The role of the integrated testing activity is to bound the flux of radionuclides that pass through the engineered barrier system/near-field environment. The purpose of this activity is to measure and model (a) the potential for transport of radionuclide elements from the waste form through the introduced materials, (b) their alteration products, and (c) the altered host rock that will make up the post-emplacement near-field environment of the potential repository at Yucca Mountain. Experimental measurements will be combined with conceptual and mechanistic

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models to bound the concentrations of radionuclide elements that will be released from the engineered barrier system/near-field environment. The estimated releases will be used in the performance assessment of the engineered barrier system/near-field environment subsystem to calculate the source term to be used in total system performance assessment.

Since the last reporting period, no new experimental measurements have been made. Previously collected experimental conservative transport data that were summarized in Progress Report #13 (DOE, 1996j) were reported (Viani and Carman, 1996).

Subactivity 1.5.5.1.1 - Radionuclide distribution in tuff wafers. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.5.5.1.2 - Radionuclide distribution in tuff cores. After the period of substantially complete containment, the various materials that will make up the engineered barrier system/near-field environment will control the transport of radionuclides released from the waste form. The materials will thus strongly influence the source term to be used in performance assessment calculations. No progress was made during the reporting period; this was an unfunded activity.

Forecast: Work is in progress to synthesize previous results in this activity to be included in a future revision of the Near-Field and Altered Zone Environment Report (Wilder et al., 1996).

6.10.12 Performance Assessment Activity 1.5.5.2 - Radionuclide Transport Modeling in the Near-Field Waste Package Environment

The objective of this activity is to use the flow and transport model for hydrologic representation of the near-field host rock developed in Design Studies 1.10.4.1 through 1.10.4.5 (Sections 5.2.2 through 5.2.6 of this progress report). The model will be validated using data from integrated testing activities and tracer tests planned in the ESF.

Subactivity 1.5.5.2.1 - Validation of near-field transport model using laboratory and field experimental data. Near-field transport of waste package releases was modeled using the total system performance assessment computer code RIP (Golder, 1995 and 1996) in support of the Engineered Barrier System Performance Requirements Systems Study (CRWMS M&O, 1996s), which is discussed in Section 4.1.19 of this progress report.

Forecast: No activity is planned for FY 1996.

Subactivity 1.5.5.2.2 - Application of near-field transport model to waste package releases. No progress was made during the reporting period; this was an unfunded activity.

Forecast: No activity is planned for FY 1997.

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6.11 SEAL PERFORMANCE (SCP SECTION 8.3.5.11)

SCP Section 8.3.5.11 addresses whether the design of the seal system will meet the requirements of 10 CFR 60.134(a) and (b) and how seal performance will contribute to the engineered barrier system performance in accordance with 10 CFR 60.113(a)(1). The seal system is defined as being composed of shafts, ramps, exploratory boreholes and their seals, and the sealing components of the underground facility.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. See Section 4.5 of this progress report for related information.

6.12 GROUND-WATER TRAVEL TIME (SCP SECTION 8.3.5.12)

SCP Section 8.3.5.12 addresses Issue 1.6, which asks whether the site will meet the performance objective for pre-waste-emplacement ground-water travel time as required by 10 CFR 60.113.

Several activities were directed at better understanding aspects of the ground-water flow system at Yucca Mountain important to performance assessment. Although specific calculations with respect to the ground-water travel time regulations may not be greatly relevant to the Project, understanding and predicting flow along fast paths is critical. The following activities examined the relative importance of scaling, heterogeneities, and alternate conceptual models in hydrologic modeling. In addition, the effects of heat on the hydrologic flow field have also been explored, focusing on the numerical formulations needed to link macroscopic models provided by the site program organization into the smaller-scale models that investigate the near-field environment. Three major deliverables were generated to document the results of these analyses. In addition, several activities associated with incomplete work from FY 1995 laboratory modeling activities were completed.

6.12.1 Performance Assessment Activity 1.6.2.1 - Model Development

The objective of this activity is to develop calculational models for predicting pre-waste-emplacement ground-water travel time.

Evaluation of Scaling Issues

In this suite of studies, numerical modeling exercises were performed at three scales (laboratory, drift, and mountain) to assess a number of issues of importance to performance assessment (Altman et al., 1996b). The following were of particular interest:

1. Assessment of methods of upscaling from the laboratory to drift scale

2. Sensitivity of certain parameters to imbibition
3. Sensitivity of percolation at the potential repository horizon to infiltration at the ground surface
4. Assessment of the range of percolation rates
5. Assessment of other possibly important processes to performance assessment analyses.

Several averaging techniques and a bulk upscaling method were used to assess upscaling methods using a laboratory imbibition experiment on a slab of tuff from TSw. Both methods were successful in approximately reproducing the laboratory results. Geometric averaging turned out to be the best of the different averaging techniques, implying that the heterogeneous domain for this TSw slab is spatially uncorrelated. The unsaturated rock matrix permeability and the van Genuchten parameters a and b (van Genuchten, 1980) were calculated using the bulk upscaling method. Comparison of the two methods demonstrate that using van Genuchten parameters generated from desaturation data on an imbibition experiment results in underestimating b .

The modeling studies showed that imbibition was sensitive to variations in matrix permeability and van Genuchten parameters. Matrix heterogeneities near the fracture also strongly affected imbibition. The drift and mountain scale models were also sensitive to variations in these parameters. These parameters need to be further constrained. Matrix permeability is assumed to increase with the scale of the model, however, the maximum element volume above which matrix permeability will not increase needs to be determined.

The magnitude of the percolation flux at the potential repository horizon is directly related to the magnitude of the infiltration at the ground surface. Preliminary two-dimensional simulations, including thin (as thin as 1 m) discontinuous layers in the Paintbrush nonwelded tuff (PTn) in the models, have shown that for low surface waste infiltration rates the PTn can divert as much as 50 percent of the water away from the potential repository. At the revised higher surface water infiltration rates, most of the water is expected to percolate vertically to the potential repository horizon. Three-dimensional modeling has also shown that the distribution of flux at the potential repository horizon can also influence whether or not water will flow laterally. Other parameters that have a strong influence on the flux with depth are matrix permeability and fracture-matrix interactions.

Of the processes shown to be important for performance assessment analyses, the effects of transient infiltration pulses on fast-path flow are particularly critical. Also important to adequate fast-path flow modeling is a better understanding of the location and spatial density of high permeability features or fracture networks. Recommendations to performance assessment analysts based on these modeling studies include the following:

1. It is important to take into account spatial heterogeneity of flow and transport processes

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2. Transient infiltration pulses need to be included in performance assessment calculations
3. Fracture-matrix interactions are clearly critical to flow through the mountain and must be incorporated into the performance assessment conceptual models
4. Thin layers within the PTn could influence the flux at the potential repository horizon and must be included (or their effects on flux with depth must be included) in performance assessment models.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.12.2 Performance Assessment Activity 1.6.2.2 - Verification and Validation

The objective of this activity is verification of computer codes and validation of mathematical model for ground-water travel time analyses.

Flow Model Validation Close-Out Activity

The following activities were accomplished in support of the flow model validation close-out project:

1. Reports on conceptual models for isothermal flow in unsaturated fractured rock (Glass et al., 1996) and physical investigations of constitutive property scaling (Tidwell, 1996) were finalized and submitted for printing. The first report describes experimental laboratory studies focused on understanding small-scale flow processes within discrete fractures and individual rock matrix blocks. The experiments suggest modifications in dual permeability models to improve their applicability and that the continuum representations for modeling flow in fractured rocks may be inadequate. The second report describes experimental laboratory studies aimed at understanding implications of upscaling small-scale measurements of hydrologic properties for large-scale hydrologic modeling. The experiments were terminated before definitive conclusions could be reached.
2. A draft report on investigations of two-phase flow in fractures was completed and submitted for technical review (Glass et al., in prep.). This report documents the comparison of percolation modeling with unsaturated flow experiments conducted in single analog fractures.
3. Data reduction and image analysis continued for two fracture-matrix interaction data sets collected in FY 1994 and 1995. In these tests, x-ray absorption imaging was used to measure the imbibition of water from a slot fracture into thin slabs of volcanic tuff.

These experiments were designed to investigate the effects of matrix anisotropy and vertical capillary barriers on matrix imbibition and matrix diffusion. Resulting analyses indicate good experimental control was achieved in the experiments as well as reveal important insight into the effects of capillary barriers on matrix imbibition.

4. Efforts were made to organize and assimilate the scientific notebook for the Fran Ridge field study. This notebook will document results of infiltration studies conducted in the zone excavated around the Fran Ridge Heater-Block Test. Results will include three-dimensional fracture maps, water flow paths marked by dyed water, and characteristics of the applied boundary conditions. A high-infiltration test at Fran Ridge was modeled (Eaton et al., 1996) with the thermal-hydrological computer code TOUGH2 (Pruess, 1987; Pruess et al., 1991 and 1996). Results with the code's dual-permeability model agreed with the experimental measurements, but the code's equivalent-continuum model calculated only minimal fracture penetration in contrast to the actual penetration. These results indicate that for high infiltration rates the dual-permeability model should be preferred over the equivalent-continuum model.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.12.3 Performance Assessment Activity 1.6.3.1 - Analysis of Unsaturated Flow System

The objective of this activity is to determine which flow paths or sets of flow paths of likely radionuclide travel in the unsaturated zone will be used in ground-water travel time calculations.

Drift Scale Modeling

The objective of this activity is to construct a model for quantifying the flows into the drift and for input to total system performance assessment. The basic model used in the present investigation is a stochastic continuum model as an alternative model to the better known effective continuum model or the double permeability/porosity model. Recent results from characterization of the single-element heater test block, from field observations of the ESF moisture study, and from development of the unsaturated zone site-scale model are used in the generalization of a three-dimensional block with a heterogeneous distribution of permeabilities representing the TSw at the potential repository level.

Results of modeling studies suggest that the inflow rates into the drift vary spatially over three orders of magnitude along the drift wall. The steady-state rates are not very sensitive to the actual value of relative humidity in the drift. For large infiltration pulses for a limited time period, flow will seek out large permeability flow paths and allow large flows through the system, largely bypassing the matrix, and could drip into the drift. Preliminary sensitivity studies

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have been performed with the stochastic continuum model to address the spatial frequency of "fast paths" and other related issues of drift-scale modeling.

Forecast: Modeling of heterogeneous inflow into drifts will continue to provide input to performance assessment of flow and transport processes on the drift scale. The episodic pulse infiltration will be systematically quantified. The stochastic continuum model and other heterogeneous models will be used in additional sensitivity analyses to account for the spatial and temporal variability of percolation into the repository drifts.

6.12.4 Performance Assessment Activity 1.6.4.1 - Calculation of Pre-Waste-Emplacement Ground-Water Travel Time

The objective of this activity is to define performance measures and to perform related analyses of pre-waste-emplacement ground-water travel time.

The report on FY-1995 pre-waste-emplacement ground-water travel time calculations (GWTT-95) was issued (Altman et al., 1996a). The report includes the definition of the conceptual model, the selection of hydrologic parameters, and the simulation of rock properties and ground-water flow for the FY-1995 pre-waste-emplacement ground-water travel time analyses. The report was summarized in Progress Report #14 (DOE, 1996b).

Subactivity 1.6.4.1.1 - Performance allocation for Issue 1.6. No progress was made during the reporting period; this was an unfunded activity.

Subactivity 1.6.4.1.2 - Sensitivity and uncertainty analyses of ground-water travel time. See Sections 6.12.1 and 6.12.3 of this progress report.

Subactivity 1.6.4.1.3 - Determination of the pre-waste-emplacement ground-water travel time. See Sections 6.12.1 and 6.12.3 of this progress report.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.12.5 Performance Assessment Activity 1.6.5.1 - Ground-Water Travel Time after Repository Construction and Waste Emplacement

The objective of this activity is to predict the ground-water travel time to the water table using the hydrologic properties changed as a result of repository construction and waste emplacement. This is needed for comparing pre- and post-emplacement ground-water travel times to establish the extent of the disturbed zone. This objective includes developing the model domain, conceptual flow models, computational codes, model parameters, and boundary

conditions to model ground-water flow at Yucca Mountain influenced by thermally driven alterations to the hydrology.

Three-Dimensional Site-Scale Thermal-Hydrological Modeling

A three-dimensional site-scale model of the unsaturated zone at Yucca Mountain was developed to simulate the thermal-hydrological response of the geologic system to the heat generated by the emplacement of high-level radioactive waste in a potential repository (Francis et al., 1996). This work provides the first set of fully three-dimensional, mountain-scale, coupled heat and fluid flow calculations for the potential repository at Yucca Mountain.

The objectives of this study were to:

1. identify the characteristics of the potential repository that might have impacts on the thermal behavior at the site
2. develop a numerical grid that could represent these effects
3. develop model parameters that reflect best available site data
4. produce coupled thermal-hydrological calculations as functions of time and location for different thermal loads
5. provide tools that can be used in future total system performance assessments that permit the modeling of the histories of thermally driven hydrologic alterations to the ambient geohydrologic systems at the site.

The preliminary three-dimensional site-scale unsaturated zone model (Wittwer et al., 1995) was modified to include finer discretization of the region near the potential repository and to incorporate recent geologic interpretations and parameter estimates for the site. Two alternative conceptual models of fluid flow in fractured porous media, the equivalent continuum model and generalized-equivalent continuum model, were used in this study. Alternative simulations were performed using both homogeneous intraunit material properties and heterogeneous rock properties within the potential repository host unit.

Simulations using base-case assumptions regarding infiltration (average of about 0.3 mm/yr) and thermal loading (83 kW/acre) indicated that the thermal-hydrological response of the system is dominated by buoyant gas phase convection during the first 1000 years following waste emplacement above most of the potential repository. Heat transfer is enhanced above the potential repository in a zone of countercurrent two-phase flow relative to the region below the potential repository in a heat pipe. A zone of increased liquid saturation from the accumulation of condensate was simulated to form above a dryout zone, which persists for approximately 1000 years near the center of the potential repository, but may not form near the potential repository edges. Liquid flux through the potential repository may increase to several hundred times relative to ambient conditions during the heating and cooling, depending on location.

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Simulated temperature, liquid saturation, and liquid flux were presented as functions of time and vertical position for several representative locations in the potential repository block. The extent, duration, and magnitude of the temperature and liquid saturation perturbations from the potential repository were calculated to be somewhat larger for a thermal load of 100 kW/acre than in the base case, but the qualitative behavior of the system is similar. Heterogeneous material properties in the TSw result in slightly higher simulated peak temperatures at the potential repository horizon and a nonuniform distribution of condensate above it relative to the homogeneous case.

Site-Scale Thermal-Hydrologic Unsaturated and Saturated Zone Modeling

Numerical simulations of the unsaturated zone and saturated zone at Yucca Mountain were performed to gain insight into the thermal-hydrological response of the system following potential emplacement of heat-generating waste packages with an assumed heat load of 83 kW/acre (Ho et al., 1996). Several unique features were incorporated into the current analyses that aim to complement previous thermal-hydrological analyses of Yucca Mountain. First, recently obtained material data were used as a basis to develop geostatistically simulated property distributions in the models. Heterogeneous property distributions are believed to yield more realistic representations of the modeled domain. Second, alternative conceptual models of fractured porous media were used in the unsaturated zone analyses. Two equivalent-continuum models and a dual-permeability model were used to determine similarities and differences in the models that may affect the results of the calculations. Finally, a suite of sensitivity analyses that investigate the effects of different boundary conditions were performed. Results show that a significant aspect of the thermal-hydrological behavior relative to performance assessment is the generation and subsequent movement of large amounts of condensate above the potential repository.

The equivalent-continuum model predicts rewetting of the potential repository region within several thousand years as a result of the downward movement of the accumulated condensate through the matrix during cooling. The dual-permeability model predicts that a significant amount of the condensate drains through the fractures during the heating phase (<1000 years), lowering the overall water content in the system. Fluxes in the fractures caused by condensate drainage can be 100 times greater than ambient percolation in the dual-permeability model, leading to the possibility of focused flow to the potential repository. All the simulations, however, show that the generated heat is sufficient to dry the potential repository, which prevents any through-flowing liquid for a period between about 100 years and several thousand years. Therefore, simulated radionuclide release is unlikely during this period when an average infiltration of 0.3 mm/year is used. Nevertheless, sensitivity analyses show that an increase in the ambient percolation reduces the rewetting time using the dual-permeability model. An infiltration rate of 10 mm/year is sufficient to eliminate the development of a dryout zone at 83 kW/acre, and water flux at the potential repository horizon is significant during the entire thermal perturbation because of combined infiltration and condensate drainage.

The saturated zone thermal-hydrological model consists of a three-dimensional, site-scale domain, using a geologic framework model of hydrostratigraphic units below the water table and

approximating heat flow above the water table as conductive transport. Calibrated saturated zone model results indicate temperature significantly increases at the water table beneath the potential repository, implying that a heat exchange boundary condition at the water table is more appropriate in unsaturated zone modeling than the commonly assumed constant-temperature boundary. The simulated thermal plume in the saturated zone has temperatures at the water table as high as 70°C, extends up to 5 km downgradient of the potential repository, persists well beyond 10,000 years, and increases ground-water velocities by as much as a factor of two below the potential repository. Saturated zone thermal-hydrological simulation results suggest the possibility of significant geochemical and mineralogic alterations to the saturated zone system from waste heat.

A study was performed with systematic investigations of the effect of thermal loading on the moisture, gas, and heat flow in the unsaturated zone of Yucca Mountain. The simulations were performed with a two-dimensional north-south vertical cross section, using both the equivalent-continuum model and the dual-permeability modeling approaches of the TOUGH2 code (Pruess et al., 1991 and 1996). The two-dimensional model covers both unsaturated and saturated zones to investigate the effects of the water table thermal conditions.

Examination of the temperature profiles during thermal loading indicates that the location of the model bottom boundary at the water table or at 500 m below the water table does not affect repository thermal-hydrological behavior during the boiling period under thermal loading. However, the coupled unsaturated zone/saturated zone model predicts about a 30°C temperature increase at the water table. This indicates that if a fixed temperature boundary is applied at the water table, the model may overestimate the rate of cooling of the potential repository.

Thermal loading at the potential repository results in significant changes in the moisture and temperature distributions in the mountain. Strong liquid and gas flow occurs near the potential repository, which is several orders of magnitude above the ambient flow condition. With the thermal loading scenario of 83 kW/acre and the coarse grid used, the maximum temperature at the repository is 104°C for 0.1 mm/year infiltration and about 95°C for 4.4 mm/year infiltration. The average temperature of the boiling zone is about 95°C, and the boiling zone is confined to the TSw hydrogeological unit.

The intensity of the boiling and rewetting processes at the repository are controlled by the available heat and liquid at the repository horizon. For the low infiltration, the repository "dries out" after 100 to 500 years. For the rock properties used in the TSw hydrogeological unit, heat pipe conditions develop above and below the repository in 10 to 100 years. This enhances heat transfer from the repository to the water table and to the land surface. With the 0.1 mm/year infiltration, the boiling zone is very extensive. Dryout conditions develop and last about 2000 years in this case. At the higher infiltration, 4.4 mm/year, a complete dryout zone is not predicted because the percolation is higher than the available energy for vaporization. In this scenario, moisture always flows into the repository throughout the thermal loading cycle.

This study also shows that for a 4.4 mm/year infiltration, the equivalent continuum and dual-permeability modeling approaches provide similar simulation results, in terms of

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temperature and moisture flow and distributions. The only difference is that at the early times, the equivalent continuum model predicts more extensive boiling conditions than the dual-permeability model. This is because the equivalent continuum model simulates a "drier" repository condition.

Forecast: Work will continue using the three-dimensional site-scale model grid to evaluate the effects of thermal loading on ground-water travel times and three-dimensional geologic features, such as faults, on the ambient moisture, gas and heat flow in the Yucca Mountain.

6.12.6 Performance Assessment Activity 1.6.5.2 - Definition of the Disturbed Zone

The objective of this activity is to re-evaluate the definition of the disturbed zone.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13 TOTAL SYSTEM PERFORMANCE (SCP SECTION 8.3.5.13)

SCP Section 8.3.5.13 addresses Issue 1.1, which asks whether the MGDS will meet the system performance objective for limiting radionuclide releases to the accessible environment as required by 10 CFR 60.112 and 40 CFR 191.13.

6.13.1 Performance Assessment Activity 1.1.2.1 - Preliminary Identification of Potentially Significant Release Scenario Classes

The objective of this activity is to preliminarily identify significant release scenario classes for the purpose of determining data and information needs that must be supplied by the Yucca Mountain site characterization program.

A report identifying a representative set of features, events, and processes for constructing scenarios to be modeled to determine the effects of seismic activity on a potential repository at Yucca Mountain was issued (Barr et al., 1996).

Subactivity 1.1.2.1.1 - Preliminary identification of potentially significant sequences of events and processes at the Yucca Mountain repository site. See the introduction to this section.

Subactivity 1.1.2.1.2 - Preliminary identification of potentially significant release scenario classes. See the introduction to this section.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13.2 Performance Assessment Activity 1.1.2.2 - Final Selection of Significant Release Scenario Classes to be Used in Licensing Assessments

The objective of this activity is to use data and information obtained in the Yucca Mountain site characterization program to modify, if necessary, the set of significant release scenario classes developed in Performance Assessment Activity 1.1.2.1 (Section 6.13.1 of this progress report) and provide information for Performance Assessment Activities 1.1.3.1, 1.1.4.1, and 1.1.4.2 (Sections 6.13.3 through 6.13.5 of this progress report) in the preliminary phases of work.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13.3 Performance Assessment Activity 1.1.3.1 - Development of Mathematical Models of the Scenario Classes

The objective of this activity is to construct mathematical models of the scenario classes developed in Performance Assessment Activities 1.1.2.1 and 1.1.2.2 (Sections 6.13.1 and 6.13.2 of this progress report).

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13.4 Performance Assessment Activity 1.1.4.1 - The Screening of Potentially Significant Scenario Classes Against the Criterion of Relative Consequences

The objective of this activity is to identify the set of scenario classes representing the significant events and processes mentioned in 10 CFR 60.112 and 60.115.

No progress was made during the reporting period; this was an unfunded activity.

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Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13.5 Performance Assessment Activity 1.1.4.2 - The Provision of Simplified, Computationally Efficient Models of the Final Scenario Classes Representing the Significant Processes and Events Mentioned in Proposed 10 CFR 60.112 and 60.115

The objective of this activity is to provide the simplified, computationally efficient models of the final scenario classes representing the significant events and processes mentioned in 10 CFR 60.112 and 60.113.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.13.6 Performance Assessment Activity 1.1.5.1 - Calculation of an Empirical Complementary Cumulative Distribution Function

The objective of this activity is to construct an efficient, total system simulator that is capable of providing probabilistic estimates of radionuclide releases to the accessible environment, under both nominal and disturbed conditions, for 10,000 years after repository closure.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment (see Section 6.8.3 of this progress report).

6.14 INDIVIDUAL PROTECTION (SCP SECTION 8.3.5.14)

SCP Section 8.3.5.14 addresses Issue 1.2, which asks whether the MGDS will meet the requirements for limiting individual radiation doses in the accessible environment for 1000 years after waste disposal as required by 40 CFR 191.15.

6.14.1 Performance Assessment Activity 1.2.1.1 - Calculation of Doses Through the Ground-Water Pathway

The objective of this activity is to use the methodology developed for total system performance assessment (Section 6.13 of this progress report) to calculate the radionuclide transport to the boundary of the controlled area and radiation doses from drinking contaminated ground water during the first 1000 years after waste disposal.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.14.2 Performance Assessment Activity 1.2.2.1 - Calculation of Transport of Gaseous Carbon-14 Dioxide Through the Overburden

The objective of this activity is to estimate the transport time for gaseous carbon-14 dioxide from the potential repository to the land surface during the first 1000 years after waste disposal.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.14.3 Performance Assessment Activity 1.2.2.2 - Calculation of Land-Surface Dose and Dose to the Public in the Accessible Environment Through the Gaseous Pathway of Carbon-14

The objectives of this activity are to collect the necessary data on carbon-14 inventory and meteorology and to calculate upper-bound values for external and internal radiation doses. Internal radiation doses include doses from both inhalation and ingestion.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

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6.15 GROUND-WATER PROTECTION (SCP SECTION 8.3.5.15)

SCP Section 8.3.5.15 addresses Issue 1.3, which asks whether the MGDS will meet the requirements for the protection of special sources of ground water for 1000 years after waste disposal as required by 40 CFR 191.16.

6.15.1 Performance Analysis 1.3.1.1 - Determine whether any Aquifers near the Site Meet the Class I or Special Source Criteria

The objective of this activity is to determine whether any aquifers within the controlled area or within 5 km of the controlled area meet the Class I criteria as defined by the EPA Ground Water Protection Strategy of 1984 (EPA, 1984) or special source criteria as defined by 40 CFR 191.12.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.15.2 Performance Analysis 1.3.2.1 - Determine the Concentrations of Waste Products in any Special Source of Ground Water during the First 1000 Years After Disposal

The objective of this analysis is to calculate the concentration of waste products in any special-source aquifers during the first 1000 years after waste disposal.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No work is planned for FY 1997. Related work will be conducted in support of the total system performance assessment for the viability assessment (see Section 6.8.3 of this progress report).

6.16 PERFORMANCE CONFIRMATION (SCP SECTION 8.3.5.16)

This section of the progress report addresses SCP Section 8.3.5.16, Issue 1.7, on performance confirmation, which is directly related to the performance confirmation program requirements of 10 CFR 60.137.

The Performance Confirmation Concepts Study Report (CRWMS M&O, 1996jj) was completed. The objective of the study was to develop technically based recommendations, regarding the extent and content of the performance confirmation program as required by 10 CFR Part 60, Subpart F. The scope of the FY 1996 study was to focus on the performance

confirmation requirements and concepts that need to be considered in the waste package and repository design and/or operation.

Performance confirmation is defined in 10 CFR 60.2 as "the program of tests, experiments, and analyses which is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met." Subpart F of 10 CFR 60 provides general requirements for a performance confirmation program, as well as more specific requirements related to confirmation of geotechnical and design parameters, design testing, and monitoring and testing of waste packages. The study began with these requirements as regulatory constraints and expanded them to a lower level of detail so that they could be implemented in the waste package and repository design. If a regulatory constraint became overly restrictive in terms of design solutions, then that constraint was noted for potential discussion with the NRC.

Identification of Parameters

The first step in developing requirements and concepts for the performance confirmation program was to identify candidate parameters that may need to be tested or analyzed to confirm that the postclosure performance objectives will be met. These parameters were identified by considering key postclosure performance objectives (e.g., limiting 10,000 year peak dose, achieving substantially complete containment) and identifying the models used to evaluate these postclosure objectives. Once the process models were identified, the parameters used in these models were identified, resulting in a list of approximately 480 parameters.

Screening criteria (e.g., time-dependent parameter, important to waste isolation calculations, potentially affected by construction) were then developed to identify a subset of these parameters as performance confirmation parameters. A final screening of the parameters identified key parameters whose observation, monitoring, or testing could have a potentially significant influence on the design of the repository or engineered barrier system. This screening resulted in a smaller list of about 90 parameters. The parameters passing this screening process included saturated hydraulic conductivity, rock temperature, fracture and fault zone characteristics, and ground-water chemical characteristics.

Performance Confirmation Concepts

The next step in the process was to develop concepts for collecting performance confirmation information for each of the key parameters. These concepts were then organized into three major areas: (1) monitoring and testing concepts (including site, repository, and waste package concepts), (2) test facilities and support concepts (including subsurface and surface concepts), and (3) evaluation and reporting concepts. Options within each of the concepts were then identified so that a nominal case and an enhanced case could be developed for each of the concepts. The nominal option consists of a set of performance confirmation tests and functions that, in the study team's judgement, would provide adequate confidence in the ability of the performance confirmation process to meet regulatory requirements and to support accurate assessment of subsurface conditions, changes in those conditions, and proper functioning of the

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natural and engineered barriers. The enhanced option consists of a set of performance confirmation tests and functions that potentially would provide a higher level of confidence than would the nominal case. The level of confidence required will be established through additional quantitative, statistical bases in conjunction with regulatory interaction and policy direction.

Evaluation of Options and Recommended Requirements

The final steps in the process were to develop evaluation criteria and then evaluate the options against those criteria. The quantitative evaluation criteria used to develop a recommendation between the enhanced and nominal options were the absolute cost of each option and the cost differences between the options. The potential impact of the testing concepts on waste isolation was also considered in evaluating and recommending them.

The performance confirmation life cycle costs for the suite of enhanced options was estimated to be approximately \$2.2 billion, while the estimated cost of the nominal options was \$0.7 billion. This is compared with the \$0.6 billion life-cycle cost estimate for the advanced conceptual design. Additionally, no difference between the options, in terms of impact on waste isolation, was identified presuming that effective borehole and excavation seals can be developed and installed. It was also determined that adequate controls will be possible for either of the options to prevent significant long-term impacts of the performance confirmation program on waste isolation.

Given this evaluation, the study recommended specific requirements for the nominal case. Requirements were recommended for (a) performance confirmation monitoring and testing, (b) subsurface test facilities and support, and (c) surface facilities.

Note that the parameters and concepts leading to the design requirements are based on the current understanding of natural and engineered barrier processes, the mathematical models that have been formulated for these processes, the computer codes that have been developed to simulate these processes and the parameters that are required for these computer codes. Uncertainties still exist with respect to many of these processes (e.g., rock matrix and fracture flow interactions, waste package corrosion). As new understanding is gained during site characterization, construction, and operations, the process models and simulations of the processes may change. These changes could necessitate changes in the list of performance confirmation parameters which could, in turn, necessitate changes in the performance confirmation requirements.

Draft Performance Confirmation Plan

A draft Performance Confirmation Plan was included in the study report. The purpose of the plan is to provide an overview of the performance confirmation approach, performance confirmation objectives, responsibilities, a concept of operations, and schedules. The draft plan contains an annotated outline of its proposed contents. The final version of the plan will contain a definition of the test and evaluation program for confirming the confinement and waste isolation performance of the MGDS. The test and evaluations covered will include process modeling,

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performance predictions, site monitoring and testing, waste package monitoring and testing, repository monitoring and testing, test data analysis and evaluation, and performance assessment. The plan will also provide test and analysis requirements for each performance confirmation test and analysis, briefly describe test/analysis objectives, and identify responsibilities and requirements for facilities, equipment, data acquisition, evaluation, and reporting.

The draft plan includes two top-level schedules in order to recommend phasing the site characterization activities into the performance confirmation activities. The first schedule separates the complete set of testing activities into three categories. The first category consists of those tests conducted as part of the site characterization program in order to support the development of a reasonable assurance argument of waste isolation and the development of the performance confirmation baseline. This category is currently ongoing and will phase out as the development of the performance confirmation program becomes complete. The second category consists of other testing, including site characterization testing in support of a site recommendation, testing to show conformance of the design to the requirements, preclosure safety testing, etc. This category of tests is also ongoing, and certain aspects of this testing activity are expected to continue through the waste emplacement period. The third category consists of testing conducted in support of the performance confirmation program. This activity is scheduled to begin at the time of the viability assessment before the end of site characterization, and to phase into a full program at about the time of license application. The second schedule provides a top level view of the data flow between the waste isolation reasonable assurance testing, the performance confirmation testing activities, total system performance assessment, and the activities required to plan and develop the performance confirmation program.

Forecast: A performance confirmation follow-on system study is planned for FY 1997. The purpose of this study will be to supplement performance confirmation program requirements important to repository design identified in the FY 1996 performance confirmation concepts study with the remainder of the performance confirmation requirements. The study will also establish the required contents of a reference performance confirmation baseline and develop a draft baseline. Finally, the study will develop Revision 0 of the performance confirmation program plan using the draft plan developed in FY 1996 as a starting point. This study will describe the performance confirmation program (contained in the performance confirmation plan) to be included in the License Application Plan. The study will also support development of a conduct of operations (Chapter 11 of the Project Integrated Safety Assessment) by outlining the operations necessary to conduct the performance confirmation program. The development of the performance confirmation program plan, the performance confirmation requirements, and the draft performance confirmation baseline will also facilitate the process of achieving compliance with the 10 CFR Part 60 requirement to begin performance confirmation during site characterization.

**6.17 U.S. NUCLEAR REGULATORY COMMISSION SITING CRITERIA
(SCP SECTION 8.3.5.17)**

SCP Section 8.3.5.17 addresses Issue 1.8, which asks whether demonstrations for favorable and adverse conditions can be made as required by 10 CFR 60.122.

No progress was made during the reporting period; this was an unfunded activity.

Forecast: No activity is planned for FY 1997.

**6.18 HIGHER-LEVEL FINDINGS - POSTCLOSURE SYSTEM AND TECHNICAL
GUIDELINES (SCP SECTION 8.3.5.18)**

SCP Section 8.3.5.18 addresses Issue 1.9, which asks whether the higher-level findings required by 10 CFR Part 960 can be made for the qualifying condition of the postclosure system guideline and the disqualifying and qualifying conditions of the technical guidelines for geohydrology, geochemistry, rock characteristics, climatic changes, erosion, dissolution, tectonics, and human interference.

During the reporting period the DOE developed a draft Notice of Proposed Rulemaking to amend 10 CFR Part 960 by adding a new site-specific subpart for Yucca Mountain. The proposed amendment would, in part, eliminate explicit evaluation of the discrete technical guidelines under this system guideline and the system guideline would be superseded by a new postclosure system guideline. A determination of compliance with the new system guideline, equivalent to a high-level finding, would form part of the basis for evaluating the suitability of the Yucca Mountain site for development as a repository.

Forecast: The Notice of Proposed Rulemaking will be published in the Federal Register and enter a period of public comment and public hearings. Following resolution of the public comments, the amended regulation will be submitted to the NRC for concurrence. A final rule is expected in late FY 1997.

6.19 COMPLETED ANALYTICAL TECHNIQUES (SCP SECTION 8.3.5.19)

The purpose of this section is to identify analytical techniques and related process models and computer codes that were completed or acquired during this and prior reporting periods and that are being used or could be used to conduct pre- and postclosure performance assessment analyses.

The compilation in Table I-1, in Appendix I, is expected to provide a quick overview of available models and codes. Progress with respect to model and code development, improvement, testing, verification, and validation during this reporting period is described in other sections of this progress report. Table I-1 includes mathematical models and computer

codes that may need to be modified as new site information becomes available, as the engineered system design develops, and as new understanding of natural and engineered barrier characteristics and processes is gained. The listed codes and models may need additional verification and validation before they will be approved for use in a license application for an MGDS at the Yucca Mountain site.

Some of the listed computer codes are being used in support of MGDS design and Yucca Mountain site characterization and are not yet used in performance assessment analyses. They are listed because they could be used to support future performance assessment analyses. Some of the computer codes are not being used and funded at present. Not all computer codes are expected to be used in support of the license application. Also, a single table is presented rather than separate pre- and postclosure tables because some of the computer codes are used or could be used for both pre- and postclosure performance assessment analyses.

6.19.1 Postclosure Performance Assessment Analytical Techniques

See the preceding introductory text of Section 6.19 and Table I-1 in Appendix I.

6.19.2 Preclosure Performance Assessment Analytical Techniques

See the preceding introductory text of Section 6.19 and Table I-1 in Appendix I.

6.20 ANALYTICAL TECHNIQUES REQUIRING DEVELOPMENT (SCP SECTION 8.3.5.20)

The purpose of this section is to discuss (a) the need to develop analytical techniques for those areas where well-developed methods (as listed in Section 6.19 of this progress report) are currently not available and (b) the verification of computer codes and validation of mathematical models on which the methods are based.

SCP Section 8.3.5.20 lists the following five subsections: (1) analytical techniques, (2) plans for verification and validation, (3) verification of analytical techniques, (4) model validation, and (5) validation program. Descriptions of model and code development, improvement, testing, verification, validation, and applications during this reporting period, however, are covered both in other sections of this chapter and in other chapters. Table I-2, in Appendix I, lists sections of Progress Report #15 where activities are described that mention the computer codes listed in Table I-1. To establish a one-to-one correspondence between these two tables, all computer codes listed in Table I-1 are also listed in Table I-2, although some of them may not have been identified in other sections of this progress report.

6.21 SITE IMPACT EVALUATIONS

The objective of site impact evaluations is to identify any potentially adverse effects of site characterization activities on the postclosure performance of a potential high-level radioactive waste repository at the Yucca Mountain site. These evaluations are documented in determination of importance evaluations (see Section 2.3.2 of this progress report), which include test interference evaluations and which establish control requirements intended to limit adverse impacts of site characterization activities on waste isolation. Site impact evaluations are required by 10 CFR 60.15(c)(1), which states that "investigations to obtain the required information shall be conducted in such a manner as to limit adverse effects on the long-term performance of the geologic repository to the extent practical."

Site impact evaluations are performed to estimate the potential effects of site characterization activities, including the construction and operation of the ESF, on testing and the waste isolation capability of the Yucca Mountain site. Controls on activities are established to limit adverse effects, if needed, based on these technical analyses. Evaluations during this reporting period include (a) a revised analysis of subsurface water use in the ESF, (b) the discharge and loss of organic materials at the site surface, and (c) the use of committed concrete in the subsurface ESF. The previously established limits for underground water use (CRWMS M&O, 1995g) are being revised in light of a new compilation of hydrogeologic properties for Yucca Mountain (CRWMS M&O, 1996f) and updated process models. The analysis of the use of organic materials that may be lost to the geologic environment at the site surface is in support of an effort to consolidate the many specific evaluations for surface-based testing activities into a single, comprehensive evaluation. Work concerning the use in the subsurface ESF and potential repository of committed concrete (i.e., concrete that will remain underground in a potential postclosure repository) is being pursued in an attempt to bound the geochemical effects of such materials on the potential repository performance.

6.21.1 Tracers, Fluids, and Materials (excluding water)

Committed Surface Organics

Current control requirements limit the use of organic-based tracers, fluids, and materials for use at the site surface to a quantity equal or less than the natural observed variation in the geologic system. Until recently an extensive study on the interactions between organic matter deposited at the site surface with the subsurface had not been conducted. During this reporting period, the surface to subsurface interactions of organic carbon were evaluated.

As a basis for the new evaluation, the duration of the geochemical effects of organic tracers, fluids, and materials added to the site surface during construction and characterization activities was compared with the impact on the geochemical system that would occur over a regulatory time frame (10,000 to 100,000 years) from additional organic matter being naturally introduced into the subsurface because of increased moisture and a cooler climate (i.e., climate change). Results of the evaluation indicate that (a) there is no potential for the level of dissolved

organic carbon in the ground water to increase, (b) the impacts due to CO₂ formation by organic matter degradation upon dissolved inorganic carbon in the ground water, dissolution or precipitation of carbonate, and weathering of rock material in the subsurface are limited to relatively short time frames, and (c) the controls currently in place are unnecessary and can be relaxed or removed.

Underground Use of Committed Cementitious Materials

A strategy is planned to address potential postclosure performance issues concerning use of large quantities of committed cementitious materials within the potential waste-emplacement drifts (e.g., precast concrete lining segments). This strategy includes performance analyses of the consequences caused by geochemical effects of these materials reacting over geologic time and incorporating constraints on (a) the potential geochemical effects inside the drift (e.g., pH, mineral dissolution/precipitation); (b) the potential geochemical effects in the geosphere (e.g., cement fluid-driven rock alteration); (c) the impacts to performance parameters from the identified potential geochemical effects inside the drift (e.g., increased solubility limits, generation of colloids); and (d) the impacts to performance parameters from the identified potential geochemical effects in the geosphere (e.g., reduced radionuclide sorption, porosity/permeability changes). This work would consist mainly of summary reports of existing data and modeling studies of the processes involved. Work was begun in a number of these areas at the end of FY 1996.

6.21.2 Water Management Criteria

Control of water use during site characterization is necessary to ensure that the conduct of these activities does not affect some characteristic that may be important to the postclosure performance of a potential repository. The control requirements and supporting analyses were documented in determination of importance evaluations (see Section 2.3.2 of this progress report).

The primary focus of site impact evaluations for water management was the revision of subsurface water use analyses (CRWMS M&O, 1995g). Analyses addressing the adverse effects on potential repository performance of water consumption (i.e., the water discharged and not recovered) are used to control the quantity and distribution of water consumption such that the identified adverse effects are negligible. The revision of this set of analyses was prompted by the recent compilation of hydrogeologic properties for Yucca Mountain CRWMS M&O, 1996f). The new summary of hydrogeologic data based on U.S. Geologic Survey lithologic units (Buesch et al., 1996a) was used in conjunction with revised analyses for the potential effects of water consumed during construction and testing operations in the ESF. The revised analyses were split into three basic groups:

1. The effects of added ESF water on phenomena at or near potential waste package emplacement locations. The behavior of water near potential waste package emplacement zones considers the changes to ambient conditions to processes such as

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waste package corrosion and diffusive and advective radionuclide transport. This analysis focuses on the effects over relatively small spatial regions. Existing statistical variations in ambient hydrogeological conditions and properties, as they affect processes important to near-field repository performance, were considered in comparison with the potential perturbation to these processes from added water.

2. The effects of ESF water on phenomena related to migration of aqueous radionuclides through the unsaturated zone. This analysis considers the effects of added water on the travel time of a dissolved, nonreactive species moving down from the potential repository zone to the ground-water table.
3. The removal of water from the ESF through evaporation of water into the forced-ventilation air flow. This analysis is used to quantify certain uses of water that may be expected to be removed through evaporation into the forced-air ventilation flow. The application target for this analysis is the use of dust control water on the ESF concrete inverts. When applied in small quantities and confined to the concrete invert, relatively rapid evaporation (over the course of 24 hours) may be demonstrated for application to a limited contiguous length of invert. The advantage afforded by this evaluation is that the discharged water may be consumed without having to include this water as part of the cumulative total "lifetime" limit for water consumption in the ESF.

As compared with the previous analyses, the revised analyses indicate that comparable, but slightly larger, limits on water use are adequate to limit adverse effects on postclosure repository performance. The technical analyses just described are complete and are expected to be issued in a revision to the subsurface Exploratory Studies Facility Determination of Importance Evaluation early in FY 1997.

Forecast: Water use in subsurface testing, particularly the thermal test facility, will require a new evaluation to address the use of wet drilling and water loss for a high-density borehole pattern associated with the heated drift test. Furthermore, the evaluations to date for ESF will have to be reworked or modified to address the effects of added water during construction of potential repository emplacement drifts. Continuing work concerning the effects on potential repository performance of committed concrete in the subsurface environment will be a part of the integration and abstraction/testing effort for both near-field geochemical waste-form mobilization modeling.

CHAPTER 7 - EXPLORATORY STUDIES FACILITY DESIGN AND CONSTRUCTION

INTRODUCTION

The Exploratory Studies Facility (ESF) is being designed and constructed to allow the performance of a program of in situ exploration and testing above, at, and below the depths at which waste might be emplaced. This work will be used to determine the suitability of the Yucca Mountain site for the construction of a potential underground high-level nuclear waste repository. This work also addresses the 10 CFR 60.15(b) requirement for in situ exploration and testing at the depths at which waste would be emplaced. Generally, the ESF will provide access to underground tuff horizons to obtain technical data.

For discussion purposes, ESF work can be divided into two parts. The first part is design of the equipment and processes necessary to perform the ESF functions. Basically, this is design to support excavation activities, including design of utilities and support equipment. The second part is the construction and excavation that implements the design. This chapter reports progress in these areas. Testing and analysis activities conducted in the ESF during this reporting period are described in Chapters 3 and 5 of this progress report.

Background

The Site Characterization Plan, (DOE, 1988), described an Exploratory Shaft Facility that would be used to gather site data through testing in a localized subsurface facility accessed by two vertical shafts. This facility would have been located in the northeast quadrant of the primary area

Title I refers to preliminary design, Title II refers to the definitive design that follows Title I, and Title III refers to construction engineering design that provides sufficient detail to support field work.

identified for potential repository construction. In consultation with the U.S. Nuclear Regulatory Commission and the Nuclear Waste Technical Review Board, U.S. Department of Energy (DOE) management subsequently decided to study alternative configurations for the ESF and the Geologic Repository Operations Area. The results were documented in a report entitled Exploratory Studies Facility Alternatives Study: Final Report (Dennis, 1991). One alternative configuration, called Option 30, was judged to be the most desirable overall concept. After several minor modifications, detailed in a document entitled Documentation of the Evaluation of Findings of the ESFAS Used to Develop a Reference Design Concept (DOE, 1991), the revised Option 30 configuration was used to form the basis for a revised Title I ESF design effort. At that time, the facility was renamed the Exploratory Studies Facility. The Title I design was described in the Title I Design Summary Report for the Exploratory Studies Facility (DOE, 1992). This configuration was also described in Sections 1.3.1 and 2.1.2 of Progress Report #8 (DOE, 1993b).

Title II ESF design began in fiscal year (FY) 1992. Early activities centered on the design of north portal surface facilities. Underground ESF Title II design began in FY 1993, concurrent

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with the start of repository advanced conceptual design. Early in repository and Title II ESF design, the ESF Option 30 layout was adjusted. This adjustment resulted in access ramps with flatter grades to support underground facility access by rail, flat-lying emplacement drifts, and emplacement drift arrangements that to a great extent avoid the Ghost Dance fault. The change to this configuration was detailed in Section 2.1.9.3 of Progress Report #9 (DOE, 1994g).

Title II ESF design was divided into design packages to allow phased design and construction. These design packages are referenced throughout Chapter 7. Where applicable, design elements have been subdivided further to meet the needs of the constructor. Plans for development of design packages for the Thermal Test Area adjacent to the north ramp extension, Calico Hills level north ramp, and Calico Hills level main and cross drifts were deleted with the implementation of the Civilian Radioactive Waste Management System Program Plan, Revision 1 (DOE, 1996a). Table 7-1 gives the package identification, lists the elements of each design package, and provides the completion status of each package as of the end of this reporting period. Figure 7-1 shows the general physical locations within the ESF of the work supported by the design packages.

During the last reporting period, a common nomenclature was established for existing and planned ESF alcoves. This nomenclature will be used for testing and other purposes. Previously, alcoves were identified by planned physical construction sequence. The new identification system replaces the numerical identifier system with a functional test-based nomenclature. The new ESF alcove names, given in Table 7-2, have been incorporated into the design package identification and descriptions provided in Table 7-1 and will be used in future documentation.

Summary of Activities During this Reporting Period

The main focus of ESF work during this reporting period was to continue tunnel boring machine excavation and test alcove excavation, while constructing only the surface support facilities necessary to support subsurface construction. By the end of this reporting period, tunnel boring machine excavation was 174 m and 27 calendar days ahead of the schedule promulgated in Revision 1 of the Civilian Radioactive Waste Management Program Plan (DOE, 1996a).

Design work continued to support tunnel boring machine excavation, and designs were issued for construction for the remainder of the Topopah Spring level main drift, south ramp, and south portal pad and facilities. Also, designs for the Thermal Testing Facility and the Northern and Southern Ghost Dance fault access drifts were issued for construction to support planned test activities in the ESF.

As noted in Progress Report #14 (DOE, 1996b), by early in FY 1996 the tunnel boring machine was greatly exceeding scheduled production rates. Several scenarios were developed that were intended to continue tunnel boring machine excavation beyond Station 39 + 40 (3940 m). A scenario was selected with key elements that included the following tasks that were not part of the initial FY 1996 baseline:

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Table 7-1. Design Package Identification and Description

Design Package	Design Package Description	Status
1	North Portal Site Preparation and Surface Facilities	
1A	<p>Elements include</p> <ul style="list-style-type: none"> • North portal pad • Topsoil storage area • ESF access road • Sewage collection and treatment system • North portal pad water supply system • Tunnel boring machine starter tunnel • Rock storage area • Switchgear building • Modifications to switchgear building for the integrated data and control system • North portal pad power distribution system (partial) • Local controls for water system 	Issued
1B	<p>Elements include</p> <ul style="list-style-type: none"> • Change house building • Shop building • Sanitary sewer system • Power distribution system • Water distribution system • Subsurface wastewater system • H-road, site grading, and paving • Site grounding • Redesigned north portal pad drainage • Reconfiguration of north portal pad for surface rail • Completion of grading and paving plan and surface rail • North portal pad perimeter fencing • North portal lightning protection 	Issued
1C	<p>Elements include:</p> <ul style="list-style-type: none"> • Compressed air system • Standby power system • Site lighting (partial) • Site grounding (partial) 	Issued

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Table 7-1. Design Package Identification and Description (continued)

Design Package	Design Package Description	Status
1D	Elements include <ul style="list-style-type: none"> • Site grounding (continuation) • Muck storage area • Conveyor maintenance access road • Fuel storage system • Site lighting (continuation) • Equipment foundations • Compressed air system condensate collection system 	Issued
1E	Elements include <ul style="list-style-type: none"> • Standby/auxiliary power • Site grounding (continuation) • ESF electrical distribution (continuation) • Revised fuel storage system 	Issued
Integrated Data and Control System	Elements include <ul style="list-style-type: none"> • Procurement specification for the complete integrated data and control system • Fiber-distributed data interface for first phase of integrated data and control system 	Issued
2	North Ramp Excavation - Starter Tunnel to Topopah Spring Level	
2A	Elements include <ul style="list-style-type: none"> • Surface and subsurface conveyor • Electrical switchgear, transformers, and power centers 	Issued
2B	Elements include <ul style="list-style-type: none"> • Utility systems • Tunnel ventilation specifications and drawings • Rail haulage system • Mapping platform procurement specification • Excavation, ventilation, and muck storage trade studies • Control system specification and drawings • Life safety monitoring and warning system 	Issued

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Table 7-1. Design Package Identification and Description (continued)

Design Package	Design Package Description	Status
2C	<p>Elements include</p> <ul style="list-style-type: none"> • North ramp to Topopah Spring level excavation and ground support • Remaining utility systems for north ramp • Electrical power, lighting, and grounding • Associated test and operational support alcoves 	Issued
(a)	Topopah Spring level main drift	Issued
(a)	<p>Ghost Dance fault accesses (at Topopah Spring level)</p> <ul style="list-style-type: none"> • Northern Ghost Dance Fault Alcove (Alcove #6) <ul style="list-style-type: none"> - Northern Ghost Dance Fault Access Drift (first 95 meters of excavation) - Northern Ghost Dance fault drill/test room (remaining approximately 50 meters of excavation) • Southern Ghost Dance Fault Alcove (Alcove #7) <ul style="list-style-type: none"> - Southern Ghost Dance Fault Access Drift (first 120 meters of excavation) - Southern Ghost Dance fault drill/test room (remaining approximately 60 meters of excavation) 	<p>Issued</p> <p>FY 1997</p> <p>Issued</p> <p>FY 1997</p>
(a)	North ramp extension (Referred to as "ESF East-West Drift" in Draft CRWMS Program Plan, Revision 1)	Out-year
(a)	<p>Thermal testing area</p> <ul style="list-style-type: none"> • Thermal Testing Facility (Alcove #5) <ul style="list-style-type: none"> - Thermal Testing Facility (access/observation drift) - Thermal Testing Facility (thermomechanical alcove) - Thermal Testing Facility (cross drift to beginning of heated drift) - Thermal Testing Facility (heated drift) 	<p>Issued</p> <p>Issued</p> <p>Issued</p> <p>FY 1997</p>
(a)	Topopah Spring level south ramp	Issued
(a)	South Portal pad and facilities	Issued

(a) The package number designations for these packages were previously deleted as discussed in Progress Report #12 (DOE, 1995h). In the future, these packages will be referred to by their names only.

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Figure 7-1. Exploratory Studies Facility Design Package Locations

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Table 7-2. Exploratory Studies Facility Nomenclature

Alcove name	Accepted alcove acronym	Construction sequence alcove number (for informal reference)
Upper Tiva Canyon Alcove (Anisotropic)	UTCA	Alcove #1
Bow Ridge Fault Alcove	BRFA	Alcove #2
Upper Paintbrush (Non-Welded) Contact Alcove	UPCA	Alcove #3
Lower Paintbrush (Non-Welded) Contact Alcove	LPCA	Alcove #4
Drill Hole Wash Fault Alcove (Deferred)	DWFA	Deferred
Thermal Testing Facility	TTF	Alcove #5
Northern Ghost Dance Fault Alcove	NGDFA	Alcove #6
Southern Ghost Dance Fault Alcove	SGDFA	Alcove #7

- Design the remainder of the Topopah Spring level main drift and the entire south ramp [from Station 56 + 00 (5600 m) to the south portal at approximately Station 78 + 58 (7858 m)]
- Design the south portal pad and access road
- Perform construction support activities required by and associated with this additional work
- Provide support from systems engineering, scientific programs, site support, quality control, and environmental, health and safety required by and associated with this work.

This scenario was incorporated into a Change Request that was initially approved by the Yucca Mountain Site Characterization Project (Project) Change Control Board in January 1996 contingent on the final detailed cost and schedule impacts. The detailed cost and schedule impacts were incorporated into a follow-up Change Request that was approved by the Project Change Control Board in February 1996. A condition of approval was that another Change Request be developed and submitted that would permit tunnel boring machine operations to continue past Station 39 + 40 (3940 m) on a 3 shift-per-day, 5 day-per-week schedule pending identification of funds. This Change Request was submitted to the Project Control Change Board and approved in May 1996.

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Construction of underground support and utility facilities continued at a rate needed to support the progress of the tunnel boring machine. The initial phase (approximately 170 m of excavation) of the Thermal Testing Facility and the Northern Ghost Dance Fault Access Drift (approximately 95 m of excavation) portion of the Northern Ghost Dance Fault Alcove were completed.

Work performed on the drawings for the ESF/Geologic Repository Operations Area is discussed in Section 4.1 of this progress report.

7.1 EXPLORATORY STUDIES FACILITY DESIGN

ESF design activities proceeded in support of ESF construction and tunnel boring machine operations. The following subsections describe the initiatives and other activities on the various design packages that occurred during this reporting period.

7.1.1 Quality Assurance Improvements

Quality assurance (QA) activities during the current reporting period included surveillances from the Project-level QA organization (Yucca Mountain Quality Assurance Division), the Civilian Radioactive Waste Management System Management and Operating Contractor (M&O) QA organization, or both simultaneously. Some surveillances identified deficiencies, but none were considered serious. ESF design personnel made a sustained effort to resolve all outstanding QA issues. Table 7-3 summarizes the ESF design quality assurance activities during the period. In general, most new deficiencies were related to the translation of the design into field activities. Specifically, deficiencies with the nonconformance reporting process and with drilling-and-blasting criteria were identified.

Work continued to upgrade the appropriate design documents to the augmented/graded QA program that was developed and approved during the last reporting period. The augmented/graded QA program has reduced cost while maintaining quality by focusing resources on the most important activities and by eliminating reviews that add little or nothing to quality.

Steel set, wet shotcrete, and dry shotcrete design specifications were revised during this reporting period to reflect the graded quality assurance approach. Release of these three specifications completes the upgrade effort for existing design documents. Revisions of associated constructor procedures and inspection matrices were also made to ensure a complete and consistent implementation package.

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Table 7-3. Exploratory Studies Facility Deficiencies

Graded Deficiencies Received by the Exploratory Studies Facility Design Organization - Issuing Organization	Deficiencies Outstanding as of 4-5-96	Deficiencies Outstanding as of 9-30-96
Corrective Action Requests (most significant)	None	None
Deficiency Reports - Yucca Mountain Quality Assurance Division	2	4
Deficiency Reports - M&O Quality Assurance	4	1
Performance Reports (least significant--isolated) - Yucca Mountain Quality Assurance Division	1	0
Performance Reports (least significant--isolated) - M&O Quality Assurance	2	1
TOTALS	9	6

7.1.2 Design Progress

The following paragraphs report progress made during this reporting period in completing ESF design.

Design Package 1 (North Portal Site Preparation and Surface Facilities)

Two design modifications for Design Package 1 were completed, baselined, and issued for construction by Engineering Change Request: (1) extension of the muck storage area east of existing north portal pad to the access road and (2) revisions to utility drawings to reflect minor changes in the design made during construction of the north portal pad utility systems. Other miscellaneous Engineering Change Requests were completed to incorporate outstanding changes into revisions of design drawings and specifications.

Integrated Data and Control System

Design personnel were responsible for design and engineering support of the ESF Principal Investigator's data collection system, including the following activities:

- Engineered, configured, and issued for construction the portable data acquisition system used for psychometric readings in the ESF.
- Rescoped equipment purchased in FY 1995 to support the single-heater test.

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- Engineered, configured, and issued for construction the large-scale data acquisition system for the single-heater test, and
- Provided direct engineering and test startup assistance to the Test Coordination Office.

Design Package 2 (North Ramp Excavation - Starter Tunnel to Topopah Spring Level)

Engineering Change Requests continued to modify Design Package 2 to support construction. Modifications implemented included revisions to the steel set, wet shotcrete, and dry shotcrete specifications to complete implementation of the graded quality assurance approach.

Topopah Spring Level Main Drift and South Ramp

The design to support excavation of the remainder of the main drift (from Station 56 + 00 [5600 m] to 59 + 01 [5901 m]) and the south ramp (from Station 59 + 01 [5901 m] to 78 + 78 [7878 m]) was completed and issued for construction during this reporting period. This completes the design work for the ESF main loop.

South Portal Pad and Facilities

The design package for the south portal was completed and issued for construction. The package consists of drawings for the excavation and construction of the south portal boxcut and pad, for ground support for the boxcut and portal highwall, and for the access road.

The ESF south portal boxcut/highwall stability analysis (CRWMS M&O, 1996nn) was finalized to support completion of the above design package. The size of the south portal pad was minimized, reducing costs to the project, while retaining its primary function of supporting the tunnel boring machine "holeout" (emergence from Yucca Mountain).

Thermal Testing Facility [at Station 28 + 27 (2827 m)]

The Thermal Testing Facility is being designed in phases to meet the needs of the testing organizations. The access/observation drift and thermomechanical alcove designs were released during the last reporting period. The design for the connecting drift to the beginning of the heated drift was completed and issued for construction during this reporting period. Design has been started on the heated drift, the final phase of this Thermal Testing Facility.

Northern Ghost Dance Fault Alcove [at Station 37 + 37 (3737 m)]

The initial design package (Northern Ghost Dance Fault Access Drift) for the Northern Ghost Dance Fault Alcove was completed and issued for construction. This package included plan and section drawings for the 90-m long drift along with a short mapper storage drift. Both the Northern and Southern Ghost Dance Fault Alcoves are being constructed to support the Program's efforts to characterize the Ghost Dance fault structure.

Southern Ghost Dance Fault Alcove [at Station 50 + 64 (5064 m)]

The initial design package (Southern Ghost Dance Fault Access Drift) for the Southern Ghost Dance Fault Alcove was completed and issued for construction at the end of this reporting period. This package includes location, plan, and section drawings for the 125-m long access drift along with a short turn-around drift included for constructability.

Other Design Activities

Work on the north portal highwall stability analysis (CRWMS M&O, in prep.[c]) was continued. This analysis will determine if a head wall and liner are required for long-term stability of the north portal.

Forecast for ESF design activities: The following activities are scheduled for FY 1997:

- Approval and issuance for construction of the south portal ventilation system. This system will be designed to support ongoing testing in the ESF after tunnel boring machine holeout at the south portal.
- Approval and issuance for construction of drawings and specifications for the remaining portion of the Thermal Testing Facility. Areas of work remaining include completion of the heated drift layouts, heated drift ground support design, thermal bulkhead design, and the alcove cable tray system design.
- Completion of the north portal highwall stability analysis.
- Revision of the design drawings for the Northern and Southern Ghost Dance Fault Alcoves to include the planned drill/test room layouts.
- Design, configuration, implementation, and integration of the data acquisition system required to support the drift-scale test.
- Commencement of development of architect/engineer system transition reports. These reports will evaluate each major system of the ESF and will define the minimum design and construction work required to satisfy the operational requirements of ongoing ESF testing. Six system transition reports will be completed in FY 1997 for power, communications, fire water/ fire protection, compressed air, nonpotable water, and subsurface lighting. The transition report for the "Q" ground support will begin in FY 1997 but will not be completed until FY 1998.
- Continuation of the ground support confirmation process. The ESF ground support systems will be evaluated to assess and confirm their adequacy. These evaluations will be based on comparison of the design with the results of ESF construction monitoring. Confirmation Reports covering ground support up to Station 56 + 00 (5600 m) will be released in FY 1997.

7.2 EXPLORATORY STUDIES FACILITY SEISMIC DESIGN

The purpose of this activity is to report on progress in ESF seismic design.

No further work occurred during this period in this area. Seismic design basis requirements for the ESF permanent and temporary items are documented in Appendix A of the Exploratory Studies Facility Design Requirements (DOE, 1996p). Seismic design basis requirements applicable to ESF permanent items are shown in this document as "to be verified." ESF items were designed using the appropriate seismic design basis requirements in the ESF Design Requirements.

Forecast: No activities are planned in FY 1997. Over the long term, engineering analysis based on the methodologies of the two seismic topical reports developed to date will be used to verify the seismic design basis requirements for the permanent items provided in the ESF Design Requirements. The engineering analysis and the removal of the "to be verified" items from the ESF Design Requirements document are expected to be completed in FY 1998. Upon completion of this task, the design of the ESF permanent items will be evaluated for any impacts.

7.3 EXPLORATORY STUDIES FACILITY CONSTRUCTION

Significant progress was made on the construction of the ESF. Figure 7-2 provides a schematic view of tunnel boring machine progress as of September 30, 1996. The "scheduled" progress in Figure 7-2 reflects the schedule promulgated in Revision 1 of the Civilian Radioactive Waste Management Program Plan (DOE, 1996a). This schedule was revised at the time the Program Plan revision was made to reflect the very large distance by which the tunnel boring machine was ahead of the previous schedule.

Less-than-favorable ground conditions during the latter portion of this reporting period resulted in slower than expected ESF tunnel advancement. The Thermal Testing Facility and the Northern Ghost Dance Fault Alcove were under construction at the end of the reporting period, along with the Topopah Spring south ramp.

7.3.1 Tunnel Boring Machine Operations

The tunnel boring machine continued excavating in the TSw2, crystal-poor middle non-lithophysal unit throughout most of this reporting period. The tunnel boring machine re-entered the TSw1, crystal-poor upper lithophysal unit, at approximately Station 63 + 20 (6320 m) in late August 1996. The tunnel boring machine is expected to remain in the TSw1 unit through

Figure 7-2. Tunnel Boring Machine Progress

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approximately 1000 of the remaining 1550 m to holeout at Station 78 + 78 (7878 m). The tunnel boring machine is expected to hole out near the end of the second quarter of FY 1997.

At the beginning of this reporting period, the tunnel boring machine was at Station 46 + 69 (4669 m), which was 1392 m and approximately 127 calendar days ahead of the 1994 Program Plan schedule. The tunnel boring machine advanced 1809 m during this reporting period and at the end of the period was at Station 64 + 78 (6478 m), approximately 104 calendar days and 1321 m ahead of the schedule. During this reporting period, 71 m and 23 calendar days were lost against the 1994 Program Plan schedule. As mentioned in Section 7.3, the project adopted a new Project baseline in June 1996. This new baseline schedule places the tunnel boring machine holeout date at March 27, 1997. At the end of this reporting period, the tunnel boring machine was 174 m and 27 calendar days ahead of this schedule.

The tunnel boring machine reached a Project milestone {complete Topopah Spring level main/start Topopah Spring level south ramp [Station 59 + 01 (5901 m)]} on July 2, 1996, well ahead of schedule. This station is near the beginning of the curve starting up the south ramp, as shown on Figure 7-2.

During the first half of this reporting period, the tunnel boring machine advanced at an average rate of 21.3 m per excavation day. This is considered excellent progress given that 307 steel sets were installed during that time frame. This performance was possible because of highly efficient tunneling crews and use of the muck handling conveyor system.

During the second half of this reporting period, progress slowed significantly after the tunnel boring machine encountered zones of highly fractured rock. The rate of advancement has continued to be negatively influenced by this rock unit, whose characteristics have required extensive hand mucking of material around the tunnel boring machine before the installation of inverters and ground support and almost continuous installation of steel sets for ground support.

Near the end of this reporting period, the Project identified a series of violations of the respirator policy for the ESF. Although there was no imminent danger to personnel, concern for strict compliance with policy and regulations caused Project management to call for a "stand-down" to evaluate the respirator policy and its application. Prompt action was taken to suspend tunnel boring machine operations and to investigate and correct the problem. After the problem was corrected, operations resumed.

7.3.2 Tunnel Boring Machine 500-Hour Maintenance

Early in the third quarter of FY 1996, the tunnel boring machine was shut down for five days to perform the third 500-hour maintenance. The tunnel boring machine is equipped with an hour meter that operates while the cutter head is rotating; this meter is used to determine the 500 hours of machine use. The maintenance was performed to ensure continued reliable operation and to meet the manufacturer's warranty requirements. As with the first and second 500-hour maintenance, the third 500-hour maintenance generally revealed conditions expected

for equipment subjected to the type of material that has been encountered. The next 500-hour maintenance is scheduled for the first quarter of FY 1997.

7.3.3 Test Alcove Construction

Test alcoves are being excavated to provide the project with dedicated testing areas free of construction influences to acquire data on the geologic, hydrologic, geochemical, and geothermal characteristics of the site. These alcoves are located at predetermined sites along the north ramp and the Topopah Spring level main drift. The general locations are based on specific test requirements (such as the need to investigate a fault structure). The specific locations chosen are those expected to provide maximum relevant test data acquisition while minimizing test interference. The tests conducted in these alcoves are described in Chapter 3 of this progress report.

Two test alcoves were under construction during the reporting period: the Thermal Testing Facility located at Station 28 + 27 (2827 m) and the Northern Ghost Dance Fault Alcove located at Station 37 + 37 (3737 m). Excavation of Phase I of the Thermal Testing Facility was completed in mid-June 1996. Phase I includes approximately 170 m of excavation. Of this excavation, 130 m is straight tunnel (access/observation drift) at an 11 to 14 percent gradient down slope from the Topopah Spring level main drift, and the remaining 40 m consists of side tunnels (thermomechanical alcove) off the straight tunnel. Phase II excavation of the Thermal Testing Facility began in late September 1996. Phase II consists of excavating the connecting drift to the heated drift, the niches located off this drift, and the heated drift itself. Rock bolts and wire mesh are being used for ground support in the Thermal Testing Facility. Drill-and-blast methods and an Alpine Miner are being used to excavate the Thermal Testing Facility.

Completion of the Thermal Testing Facility Phase I satisfied the Program milestone to complete Thermal Test Alcove #1 construction (first 150 m).

Excavation of the Northern Ghost Dance Fault Alcove began in late April 1996. Phase I (designated as the Northern Ghost Dance Fault Access Drift) of this alcove was completed in late August 1996. A total of 95 m were excavated in accordance with design drawings using both drill-and-blast methods and an Alpine Miner. Rock bolts and wire mesh were used for ground support. Upon completion of this excavation, a borehole was drilled from the face of the access drift to locate the Ghost Dance fault. The borehole was drilled to a length of 30 m without locating the fault. (See Section 7.3 forecast for planned work to address the fact the fault was not located after 30 m of drilling.)

Completion of Phase I of the Northern Ghost Dance Fault Alcove satisfied the Program milestone to complete excavation of first Ghost Dance fault access.

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7.3.4 Surface Facilities and Utilities Construction

Completion of two facilities on the north portal pad, deferred during the first quarter of FY 1996 because of budgetary constraints, has been rescheduled. Construction to complete the change house building will resume in FY 1997, and construction to complete the switchgear building will resume in FY 1998.

The south portal road, pad and boxcut construction began in early September. This task involves stripping the topsoil for the road and the pad, excavating the boxcut, constructing the demobilization pad for the tunnel boring machine, and setting up the utility needs for the demobilization of the tunnel boring machine operation. Details of this demobilization operation have not yet been determined.

7.3.5 Exploratory Studies Facility Tunnel Board of Consultants

The charter of the ESF Tunneling Board of Consultants has been, until this reporting period, to examine safety, cost-effectiveness, and design adequacy of ESF tunneling and underground construction activities. During this reporting period, the Board, at the Project's suggestion, redirected its emphasis toward repository rather than ESF issues.

The Board had previously visited the site in October and December 1995, and in March 1996. The Board's comments on the March 1996 site visit, received during this reporting period, indicated that safety and health issues continued to be a top priority with the Project team. Favorable comments on housekeeping practices at the site and use of personnel safety devices were provided by the Board. The tunnel dust problem (higher than permissible levels of crystalline silica dust in the air at various locations in the ESF) that the Project has recently experienced was studied, and the Board generally concurred with the actions taken to date and planned future actions.

The Board met once during this reporting period, in late June 1996. At the end of the June meeting, the Board stated that they thought their ability to further assist ESF construction activities would be limited because little is expected to occur between the present time and the holeout of the ESF tunnel that they have not already witnessed and commented on. They further stated that the Board would be more productive by helping resolve the many issues connected with the future repository design and construction. The introduction to Chapter 4 of this progress report describes the Board's past and planned activities in support of repository design and construction.

Although this visit was focused primarily on repository issues, some ESF-related discussions occurred. A general review of the constructor's contract status and the FY 1996 and FY 1997 scopes of work, including the background for current planning, led the Board to conclude that a firm project plan is in place. The Board also reported on discussions held with QA and quality control personnel. Finally, subjects related to tunnel boring machine performance were briefly discussed with M&O personnel.

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Forecast for ESF construction activities: The tunnel boring machine is expected to advance at 12 m or more per day during the first and second quarters of FY 1997. This rate of advancement is planned until excavation of the south ramp is completed and the tunnel boring machine holes out. Less-than-favorable ground conditions are expected, and the rate of advancement is expected to be somewhat slow compared with the past average daily advancement. The Project goal is to have the tunnel boring machine reach the south portal during the second quarter of FY 1997.

Because a 30-m long borehole drilled from the Northern Ghost Dance Fault Alcove access drift did not locate the Ghost Dance fault, an additional 15 m of Phase I excavation will be performed in the access drift, then the borehole will be extended to locate the fault. Upon location of the fault, a test program will be conducted. Phase II excavation, which will include excavation through the fault and excavation of the drill/test room, is scheduled to begin in the second quarter of FY 1997.

Additional alcove construction scheduled to be completed in the second quarter of FY 1997 includes Phase II of the Thermal Testing Facility (remainder of Thermal Testing Facility) and Phase I of the Southern Ghost Dance Fault Alcove (Southern Ghost Dance Fault Access Drift). Both controlled drill-and-blast methods and an Alpine Miner are planned to be used in the excavation of these alcoves.

Completion of conversion of the tunnel ventilation system after tunnel boring machine holeout is scheduled for the third quarter of FY 1997.

Construction of the south portal road, pad, and boxcut and the change house on the north portal pad is scheduled to be completed in the first quarter of FY 1997.

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APPENDIX A

Documentation of Changes to the Program Since the Site Characterization Plan
was Issued and Status of Site Investigations, Performance Assessment and
Design Activities

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APPENDIX A

Documentation of Changes to the Program Since the Site Characterization Plan was Issued and Status of Site Investigations, Performance Assessment and Design Activities

INTRODUCTION

The 1988 Site Characterization Plan (SCP) (DOE, 1988) was developed in accordance with the Nuclear Waste Policy Act of 1982 (NWPA, 1983), as amended (NWPAA, 1987), and has been the underlying basis for the site characterization phase of the geologic repository program. In 1989, the U.S. Department of Energy (DOE) assessed the progress and needs of the repository program and established a schedule that would result in a suitability determination for Yucca Mountain in fiscal year (FY) 2001, and if the site were suitable, would start disposal operations in FY 2010. In parallel with the DOE assessment, the approach to underground characterization changed as vertical shaft accesses were replaced by horizontal drifts. From 1989 to 1994, the DOE planned for and then conducted a comprehensive program of site investigations based on the SCP.

By 1994, external and internal factors had tended to broaden, rather than focus the program; Congress had also begun to express concern about continuing growth in the estimated cost of site characterization. Thus in 1994, the DOE issued a revised Program Plan (DOE, 1994a) that was designed to show early observable progress within the financial resources likely to be available. The plan recognized that a great deal of site characterization information had been obtained since the SCP was issued, and that therefore, completing the entire SCP was technically unnecessary and would also have required more resources than could reasonably be expected to be available before the submittal of a license application in 2001. As a result, a new, more flexible approach was developed and site investigations were phased in such a manner that some of the original planned tests could be de-emphasized, and others could be shifted to confirmatory status. Previous progress reports have reported these changes as they affected study plans, design activities, and performance assessment plans. The Civilian Radioactive Waste Management Program (Program) intends to continue evaluations and adjustments of work scopes as information needs evolve.

Congress endorsed the 1994 Program Plan and provided a 37 percent increase in funding for FY 1995; subsequently important progress was made. However, guidance from Congress and a significant funding reduction in FY 1996 required another revision to the Program Plan, which was issued in May 1996 (DOE, 1996a). Under the funding reductions, the 1994 Program Plan was no longer sustainable. The Yucca Mountain Site Characterization Project (Project) was refocused to emphasize core scientific activity which had continued to develop site characterization data and models throughout this period, excavation of sections of the Exploratory Studies Facility (ESF) necessary for scientific study, and completion of the repository and waste package conceptual designs. Activities supporting the preparation and filing of a license application for the repository were deferred. In FY 1997, the Program was

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further focused on an assessment of the viability of geologic disposal at Yucca Mountain in 1998. The revised program strategy is designed to maintain momentum in scientific investigations and regain target dates for determining site suitability and submitting a license application. The new date for recommending the repository site to the President is 2001 and the current plan is to submit a license application to the U.S. Nuclear Regulatory Commission (NRC) in 2002.

Reflecting these top-level program redirections in detailed annual and long-range plans was a major task during FY 1996. With a baselined program in place at the beginning of FY 1997, documenting changes from the original plans presented in the SCP is now a priority. Previous progress reports have provided linkages from the SCP to the requirements or planning documents that provide the basis for the ongoing programs, and have also documented changes to the site study and activity structure in the SCP. This appendix is intended to extend the documentation to provide a status and rationale for changes in the design and performance assessment programs. Most changes to the program will be found in the approaches to, amount of, and sequencing of field data collection activities.

While there have been noticeable changes to the repository and waste package design concepts since the SCP Conceptual Design (SNL, 1987), there has not been a correspondingly large number of substantial changes in the technical information needed to design the repository and waste package. The most significant change to the original conceptual design plans is the waste package described in the SCP. That waste package was a thin walled container designed to be emplaced in boreholes; current plans, driven in part by DOE goals for earlier waste acceptance, have shifted to a large, double-walled waste package that will be emplaced in large drifts. A number of changes in the waste package design program are linked to this change.

Similarly, as additional information about the geotechnical character of the site has become better understood, and as system studies have examined alternative approaches to address 10 CFR Part 60 requirements, the repository design concept has evolved to be responsive to this information. For example, the SCP conceptual repository design was interfaced with the ESF design that used vertical shafts for access. Current repository designs are integrated with the drift-based approach that has been used for the ESF. These changes to the current repository design, while appearing to be substantially different from the conceptual design that served as the basis for the SCP, have resulted in few substantive changes in the definition of the technical information needed to design the repository. While maturation in the understanding of constraints and design solutions has resulted in designs that are more responsive to 10 CFR Part 60 requirements, there has not been a concomitant large number of significant changes in the approaches embodied in the issue resolution strategies developed to address these regulatory requirements.

For performance assessment, changes in the regulatory framework together with new site and design information have increased our knowledge base so that improved approaches can be defined. Many of these improved approaches have been discussed with NRC staff during technical interactions or summarized in previous progress reports.

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This appendix provides a systematic review and documents the changes since the SCP was issued at a level of detail that is commensurate with the current planning basis. Following this introduction, the changes in site investigations, repository design, waste package design, and performance assessment are discussed in turn. The discussions first outline the background leading up to the changes and then provide the current status in each area.

This appendix will be updated in future progress reports as additional changes to the Program are made. While this semiannual progress report summarizes changes in the program since the issuance of the SCP in 1988, detailed documentation of the rationale and justification for these changes is still under development. As part of the ongoing annual and long-range planning efforts, we continue to evaluate our work plans to ensure that the scope and schedule for activities will support the major milestones of the Program, which are (1) viability assessment in 1998, (2) site recommendation in 2001, and (3) license application in 2002. Future semiannual progress reports will provide improved rationale and justification for changes to the program as performance and design information matures. Ultimately, the adequacy of the revised site characterization program will be judged on the basis of whether sufficient engineering and scientific information has been developed at each stage of the program to provide the technical basis for the approval required to continue the program.

Documents cited in this appendix are included in the consolidated reference list for this progress report (Appendix L).

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A.1 SITE PROGRAMS (SCP SECTION 8.3.1)

The Nuclear Waste Policy Act and the High-Level Radioactive Waste Disposal Regulations (10 CFR Part 60) specify that DOE develop an SCP before beginning any activities to characterize potential repository sites. The SCP (DOE, 1988) presents the initial general plan for the Yucca Mountain site and was based on then-available information about the site, and on then-current conceptual designs for the repository and the waste package. The plan was intended to be the framework for all the site programs, but it was also intended to provide flexibility. The framework was to be augmented by study plans that were to be developed for each study and were intended to supply specific requirements for each study. These plans were intended to describe the specific objectives of each study, specify the approaches and methods to be used to collect data, describe the accuracy and precision requirements for the data, and identify the uses for which the data were needed.

The SCP envisioned an extensive program of data collection designed to thoroughly characterize the natural features and processes of the site, and reduce, or at least bound, the uncertainties associated with the various characterization parameters. The purpose of the effort was originally to provide the scientific data needed to support the evaluation of site suitability and develop the license application for construction authorization. As discussed in the introduction to this appendix, the Project has been refocused to emphasize core scientific studies and excavation of those parts of the ESF needed for in situ scientific studies. The revised program strategy was designed to maintain momentum in scientific investigations, provide data needed to support the viability assessment, and regain the target dates for determining site suitability and submitting a license application.

In planning the program described in the SCP, the DOE adopted an approach that began with identifying the regulatory requirements that must be satisfied in siting and licensing the repository, identifying the performance and design information needed to address those requirements, and then developing specific investigations to obtain the needed information. This approach was embodied in an issue resolution strategy which was discussed in some detail in Section 8.1 of the SCP. An important part of this strategy was an issues hierarchy (discussed in Section 8.1.1 of the SCP) that consisted of key issues, issues, and information needs. The key issues and issues were based on the regulatory requirements that govern a repository. The information needs defined the data and analytical techniques that were needed to resolve each issue. The DOE expected that satisfying the information needs would resolve the issues and that resolution of the individual issues would lead to resolution of the key issues. Issue resolution was acknowledged as not needing to provide complete assurance that performance of the repository system would be acceptable. Instead, reasonable assurance of acceptable performance was, and remains, the general standard that will be met. The site characterization program and issue resolution strategy outlined in Sections 8.0 and 8.1, respectively, of the SCP were to be applied in an iterative manner to develop confidence throughout the licensing phases.

The DOE established an issues-based approach to planning site characterization in the SCP. The issues hierarchy stated questions about the performance of the disposal system and identified the information that would be required before a site could be selected and licensed. The information requirements were based on the issues-hierarchy concept presented in the

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Mission Plan (DOE, 1985). The issues hierarchy was developed as a three-tiered framework consisting of key issues, issues, and information needs. On the highest tier were four key issues which embodied the principal requirements established by the regulations governing geologic disposal. Each of the key issues was expanded, in the next tier, into a group of related issues that elaborated on the requirements stated in the parent key issue. The lowest tier consisted of still more detailed sets of requirements called "information needs" that were associated with each issue. This framework provided a convenient means to distinguish broad questions of overall performance and suitability (key issues) from more specific questions about the characteristics of the site, the design of the repository and the waste package, and the performance of the total geologic disposal system. The framework also distinguished the key issues and issues from the requirements for basic information needed to resolve the issues.

The investigations for this program have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessments, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgement and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities.

In addition major technical revisions to the repository program, including the reconfiguration of the ESF from a shaft-and-main configuration to a ramp-and-main configuration, mechanical excavation of the ESF using a large diameter tunnel boring machine, and reconfiguration of the repository from vertical borehole emplacement to in-drift emplacement, required major revisions to the site programs. The ramp-and-main configuration provided an increased number of opportunities for observation of changes in stratigraphic, lithologic, and structural characteristics of the host rock. As a result, the strategy and methods for in situ mapping of fracture networks, faults, and lithostratigraphic features have changed considerably. Most notable of these changes has been the acquisition of a large volume of data collected through detailed line surveys and full periphery mapping of the ESF. Some questions about geohydrologic features and processes, inferred from the results of surface-based tests, could be answered by direct observation. Because of the increased opportunities for direct underground observation and sampling, it was possible to reduce the scope and delete some surface-based testing activities.

Section A.1 of this appendix is organized by individual site characterization programs. The information on each program summarizes by investigation level the background and SCP plans and then reports the changes that have occurred, the basis for the changes, and the current status.

A.1.1 Geohydrology Program (SCP Section 8.3.1.2)

The geohydrology program was developed to provide an understanding of the geohydrologic environment that is essential to assessing the viability and suitability of the site. Ground water is expected to be the major transport medium of radionuclides to the accessible environment. The general SCP strategy to accomplish the geohydrology program was to conduct investigations that would result in a complete and accurate description of the pertinent components of the hydrologic system. The description would reflect an understanding of the hydrologic properties, initial and boundary conditions and processes, and their interrelationships. The results of the geohydrology program were to be combined with the results of other site programs to produce a site model, or a complete description of the site.

The geohydrology program consisted of the data-collection and evaluation activities that were to result in hydrologic models that describe two distinct regimes of the hydrologic system: the unsaturated zone and the saturated zone. Each of these regimes is impacted by the surface-water flow regime, and each was to be characterized to provide input to the hydrologic models. The unsaturated zone hydrologic model was to be developed only at the site scale, whereas the surface-water and saturated zone models were to be developed at both site and regional scales. The hydrologic regimes described by these models were to be those that significantly affect the resolution of hydrologic-related design and performance issues; these regimes, therefore, were to be the principal subjects of investigation in the geohydrology program.

The investigations included in the geohydrology program are summarized in the following sections.

A.1.1.1 Studies to provide a description of the regional hydrologic system (SCP Investigation 8.3.1.2.1)

Background and SCP Plans. The objectives of this investigation were (a) to develop a conceptual model of the regional hydrologic system to help assess the ability of the site to contain and isolate waste, and (b) to construct a consistent, regional, numerical model of ground-water flow so that reliable boundary conditions could be assigned to the more critical site area embedded within the regional model. This investigation included four studies developed to accomplish the following:

1. Study 8.3.1.2.1.1 (characterization of meteorology for regional hydrology): This study was to (a) characterize precipitation in the area surrounding Yucca Mountain and its relationship to surface runoff, with particular emphasis on the Fortymile Wash drainage basin; and (b) provide site-specific information on storm precipitation at and near the network streamflow-measurement sites as input to precipitation-runoff models and to infiltration studies.
2. Study 8.3.1.2.1.2 (characterization of runoff and streamflow): This study was to (a) collect data on the characteristics, magnitudes, frequencies, and timing of surface-

water runoff at, and peripheral to, Yucca Mountain; (b) develop an understanding of the relationships between specific runoff events and the characteristics of the storms; (c) provide calibration data for precipitation-runoff models for the regional study area; (d) provide data and interpretations of surface-water runoff for evaluations of the amounts and processes of ground-water recharge; and (e) document both quantitatively and qualitatively the characteristics of debris transported by intense surface runoff and assess the potential for flood hazards and related fluvial-debris hazards.

3. Study 8.3.1.2.1.3 (characterization of the regional ground-water flow system): This study was to (a) prioritize data needs for use in the regional ground-water flow description; (b) determine the regional potentiometric distribution, including the cause of the large hydraulic gradient; (c) characterize the regional hydrogeologic framework to support reliable estimates of ground-water flow direction and magnitude; (d) use hydrologic, hydrochemical, and heat-flow data to determine the magnitude and direction of ground-water flow; (e) determine to what extent (quantitatively, if feasible) Fortymile Wash has been a source of recharge to the saturated zone under present and past conditions; and (f) improve estimates of ground-water discharge by evapotranspiration in the Amargosa Desert to provide boundary-condition data for regional ground-water flow models.
4. Study 8.3.1.2.1.4 (regional hydrologic system synthesis and modeling): This study was to (a) synthesize available data and identify ground-water flow system boundaries, hydrogeologic units, structural controls, and other hydrogeologic features pertaining to the regional ground-water flow system; (b) update an existing two-dimensional, subregional, parameter-estimation model; (c) perform subregional, two-dimensional cross-sectional modeling to estimate ground-water flow direction and magnitude along a potential flow path through the repository block to the accessible environment and extending into the region; (d) develop a comprehensive, regional, three-dimensional numerical ground-water flow model; and (e) use the regional model to test the impacts of possible future tectonic activity and climatic changes on the saturated hydrologic system.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities.

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1. In the meteorology study (8.3.1.2.1.1), rainfall-runoff models were not developed because direct relationships between precipitation and both infiltration and recharge were developed for hydrologic models using methods that did not require simulation of the runoff component. Also, because runoff occurs so infrequently, it was determined infeasible to maintain readiness for runoff monitoring with available Project resources. Instead, the emphasis of meteorology study was on analyzing regional and synoptic-scale weather patterns that impact infiltration at Yucca Mountain and on statistically analyzing the spatial variability of average annual precipitation as it relates to estimates of ground-water recharge for the regional saturated-zone flow model. Meteorological data collection and analysis activities were concentrated on determining the seasonality, duration, intensity, and spatial variability of storms that produce net infiltration in the many small watersheds that make up the Yucca Mountain site area. To accomplish this, an intensive network of full weather stations and tipping-bucket precipitation gauges was maintained through FY 1995 and then substantially reduced in FY 1996. A reduced-intensity, site-area, meteorological data-collection effort will continue after being transitioned to the Radiological/Environmental Field Programs. The DOE believes that the site-area data collection effort will be adequate to provide data needed for the viability assessment and license application, but the determination of adequacy of the data will be based on analyses of the sensitivity of total system performance assessment.
2. In the runoff and streamflow study (8.3.1.2.1.2), regional-runoff studies and data collection for precipitation-runoff modeling were terminated before being fully implemented because the data were not needed for the regional ground-water-flow model. Regional ground-water modeling (D'Agnese et al., in press) did not require runoff data for model calibration because data describing a direct relationship between precipitation and ground-water recharge was used. In recent years, the emphasis of the streamflow study shifted to measuring the runoff component of the water balance in small watersheds at Yucca Mountain in support of the unsaturated zone infiltration study (8.3.1.2.2.1). However, because the net-infiltration component is so small compared with the runoff component and because runoff occurs so infrequently, this approach was abandoned after instrumenting only a few watersheds. Because flooding and fluvial-debris transport were shown by the preclosure hydrology program (8.3.1.16) to pose little or no threat to the ESF, the potential repository, or surface facilities at Yucca Mountain, studies to document transport of debris by severe runoff were terminated before being fully implemented.
3. In the regional ground-water system characterization study (8.3.1.2.1.3), the drilling program designed to resolve uncertainties in the regional potentiometric distribution (including the large hydraulic gradient) has not been implemented. In particular, a deep hole in the Amargosa Desert intended to establish geologic control and obtain potentiometric-head data for the Paleozoic carbonate aquifer was not drilled. Instead, data from sources outside the Project have been relied upon almost exclusively to characterize the regional hydrogeologic framework and the regional potentiometric surface for input to the three-dimensional, regional ground-water-flow model.

Although possible causes of the large hydraulic gradient have been identified through analyzing available geologic and geophysical data and through hydraulic testing in well USW G-2, the cause of this feature remains an unresolved issue (Luckey, 1996). The large hydraulic gradient is a conceptual uncertainty because there is no obvious geologic explanation and deep geologic information is sparse in this area north of Yucca Mountain. Although reconnaissance-level studies have determined that ground-water recharge to the saturated zone occurs in upper Fortymile Wash, the field studies to quantify this recharge have not been conducted. Similarly, although feasibility and prototype work was performed, the field studies to improve estimates of ground-water discharge by evapotranspiration in the Amargosa Desert have not been conducted. Instead, estimates of regional ground-water recharge and discharge were improved using a geostatistically derived distribution of average annual precipitation and a regional distribution of recharge potential that uses elevation, vegetation, slope-aspect, and soils data obtained using remote-sensing and Geographic Information System techniques.

4. In the regional hydrologic system synthesis and modeling study (8.3.1.2.1.4), updating of an existing two-dimensional, subregional, parameter-estimation model, developed in 1984, and two-dimensional cross-sectional modeling along a potential flow path have not been performed as separate activities. However, much of the work scope intended for these activities is being accomplished by the development and testing of the regional, three-dimensional ground-water flow model (Activity 8.3.1.2.1.4.4). The distribution of estimated values of hydraulic conductivity from parameter-estimation simulations of the model are well within the range of field data for the region (D'Agnese et al., 1996b), but the model still contains uncertainty. This is because field values of hydraulic conductivity range over two to three orders of magnitude for each rock type. Overall, the range of hydraulic conductivity values for the entire model is more than seven orders of magnitude. Furthermore, there are only about 20 potentiometric-level control points for the lowest layer of the model where most of the Paleozoic carbonate aquifer is represented. Note that the hydraulic conductivity of the Paleozoic carbonate aquifer was the most sensitive parameter in the parameter estimation calibration of the model (D'Agnese et al., 1996b). Also, model results indicate that flow in the Paleozoic carbonate aquifer has substantially influenced the flow in the overlying volcanic rocks. However, overall confidence in the simulation of the Paleozoic carbonate aquifer is strengthened by good control on discharge from the aquifer through well-documented spring discharge data.

The overall regional saturated zone flow system in the vicinity of Yucca Mountain appears to be controlled by the deep Paleozoic carbonate aquifer. From a postclosure performance perspective, however, the overlying tuffaceous aquifers are more significant because they would contain any likely travel paths for radionuclides moving between the potential repository and the accessible environment. In addition, any future use of ground water in the region would likely concentrate on the shallower tuffaceous aquifers rather than on the deeper, albeit more transmissive, carbonate aquifer. The uncertainty in the overall saturated zone flow system and the potential

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transport of radionuclides will be assessed in the total system performance assessments.

Although large-scale anisotropy has not been characterized by field tests, regional structural features (major faults and fault zones) have been included in the regional model to improve its performance (see Section 3.1.4 of this progress report under Activity 8.3.1.2.1.4.4). The results from ongoing sensitivity analyses will determine whether any further data collection would significantly increase confidence in the regional saturated zone model.

A.1.1.2 Studies to provide a description of the unsaturated zone hydrologic system at the site (SCP Investigation 8.3.1.2.2)

Background and SCP Plans. The objective of this investigation was to develop a model of the unsaturated zone hydrologic system at Yucca Mountain that would help assess the suitability of the site to contain and isolate waste. Developing this model requires an understanding of the manner in which water and gases move through the unsaturated zone, including the directions, paths, and rates in which flow occurs. This information was to be provided through studies of the characterization of infiltration, percolation, gaseous-phase movement, and hydrochemistry. Flow and transport modeling designed to simulate the natural system would provide sensitivity analyses to help prioritize additional data collection. This investigation includes nine studies. Of these, the first seven were data-collection studies; the last two were system-modeling studies. These studies were developed to accomplish the following:

1. Study 8.3.1.2.2.1 (characterization of unsaturated zone infiltration): This study was to (a) characterize the infiltration-related hydrologic properties and conditions of the surficial soils and rocks covering Yucca Mountain; (b) characterize present-day, natural infiltration processes and net-infiltration rates; (c) characterize the range and spatial variability of infiltration rates, flow velocities, and flow pathways in the near-surface unconsolidated surficial material and consolidated bedrock using double-ring infiltrometer and ponding studies (artificial infiltration activity); (d) characterize the relationship between precipitation, soil thickness, runoff, infiltration, evapotranspiration, and development of perched water tables in the near-surface unconsolidated surficial material in each representative hydrogeologic surficial unit using small-plot and large-plot rainfall simulation tests (artificial infiltration activity); and (e) estimate the future spatial distribution of infiltration rate over the repository block.
2. Study 8.3.1.2.2.2 (water-movement tracer tests): This study was to characterize the percolation of precipitation into the unsaturated zone at Yucca Mountain and the movement of water through the unsaturated zone using chloride and chlorine-36 measurements.

3. Study 8.3.1.2.2.3 (characterization of percolation in the unsaturated zone—surface-based studies): This study was to (a) characterize and statistically describe the flux-related, matrix hydrologic properties of major unsaturated zone hydrogeologic units and structural features as functions of moisture content or potential through laboratory testing of geologic samples obtained from surface-based boreholes and from the ESF; (b) determine the present vertical and lateral variation of percolation flux through the hydrogeologic units and structural features by measuring the potential field and determining the in situ bulk permeability of the unsaturated media in vertical boreholes throughout the site; (c) evaluate the hydrogeologic significance of fracturing, brecciation, and gouge development within the Solitario Canyon fault zone by drilling and testing a horizontal borehole; and (d) investigate the relationships between present flux and past climatic conditions.

4. Study 8.3.1.2.2.4 (characterization of percolation in the unsaturated zone—ESF studies): This study was to (a) perform ESF hydrologic tests to supplement and complement the surface-based hydrologic information needed to characterize the Yucca Mountain site and to provide information for analyzing fluid flow and the potential for radionuclide transport through unsaturated tuff; (b) combine the integrated results from the ESF hydrologic tests with data from the surface-based studies to provide an overall understanding of the unsaturated zone hydrologic system (ESF tests were designed to provide phenomenological information about water flow through unsaturated fractured tuffs, in addition to providing basic hydrogeologic data) and (c) conduct ten sets of hydrologic tests in the ESF:
 - Intact-fracture testing to evaluate fluid-flow and chemical-transport properties of single, relatively undisturbed fractures
 - Percolation testing to determine the hydrologic conditions that control the occurrence of fluid flow within fractures and matrix
 - Bulk-permeability testing to determine "representative" characteristics of fracture networks for model simulations at the scale at which the fractured host rock behaves as an equivalent porous medium
 - Radial-borehole testing to determine rock mass hydrologic properties (including bulk air permeability) and to detect vertical movement of liquid water and/or vapor within hydrogeologic units and along contacts
 - Excavation-effects testing to monitor changes to both the stress state and fractured-rock permeability caused by excavating and lining the ESF and to calibrate a coupled hydraulic-mechanical model
 - Testing of the Calico Hills nonwelded unit to determine hydrologic processes, conditions, and properties under both present and expected future conditions

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- Perched-water testing to detect any occurrence of perched-water zones, estimate hydraulic properties of the zones, and determine the implications of perched water on flux, flow paths, and travel times
 - Hydrochemistry testing to understand the gas transport processes; provide independent evidence of flow direction, flux, and travel time of gas and water; and determine the extent of water-rock interaction and the geochemical evolution of water
 - Multipurpose-borehole testing near the ESF to monitor potential interference of ESF construction with ESF tests, identify perched water, and confirm engineering and hydrogeologic properties of the rock before to ESF construction
 - Testing of hydrologic properties and flow conditions of major faults encountered in the long drifts at the main test level of the ESF.
5. Study 8.3.1.2.2.5 (diffusion tests in the ESF): This study was to determine in situ the extent to which nonsorbing tracers diffuse into the water-filled pores of the tuffs of the Topopah Spring welded unit and the Calico Hills nonwelded unit in the ESF.
 6. Study 8.3.1.2.2.6 (characterization of gaseous-phase movement in the unsaturated zone): This study was to (a) describe the pre-waste emplacement gas-flow field and its effect on net water-vapor transport from the unsaturated zone; (b) identify structural controls on gas-phase flow; (c) determine conductive and dispersive properties of the unsaturated zone for gas flow to assess potential transport of gaseous radionuclides (e.g., carbon-14); and (d) provide the parameters necessary for modeling gas flow; perform model simulations of gaseous flux of moisture affecting deep percolation and transport of tracers in the gas phase.
 7. Study 8.3.1.2.2.7 (characterization of the unsaturated zone hydrochemistry): This study was to (a) perform hydrochemical investigations to understand gas-transport mechanisms and provide evidence of gas-flow direction, flux and travel time within the unsaturated zone; (b) design and implement methods for extracting pore fluids from the tuff; (c) provide independent evidence of flow direction, flux, and travel time of water in the unsaturated zone; and (d) determine the extent of the water-rock interaction and model geochemical evolution of water in the unsaturated zone.
 8. Study 8.3.1.2.2.8 (fluid flow in unsaturated fractured rock): This study was to (a) develop and validate (through ESF testing) detailed conceptual and numerical models of fluid flow and transport within unsaturated, fractured rock; (b) apply these models to volumes of fractured rock at or below the dimensions at which the rock can be replaced conceptually by an equivalent porous medium; and (c) use the models to help design and interpret hydrologic and pneumatic tests and provide information about model parameters that can be incorporated into site-scale models (Study 8.3.1.2.2.9).

9. Study 8.3.1.2.2.9 (site unsaturated zone modeling and synthesis): This study was to: (a) develop appropriate conceptual models for the site unsaturated zone hydrogeologic system; (b) select, modify, or develop numerical hydrologic models capable of simulating the hydrogeologic system and its component subsystems; (c) construct appropriate hydrologic models for the natural site hydrogeologic system to simulate and investigate the present state of the system and predict probable future and past states of the system under changes in the environmental conditions; (d) evaluate the accuracy and uncertainty of the models using stochastic modeling, conventional statistical analyses, and sensitivity analyses; and (e) integrate data and analyses to synthesize a comprehensive, qualitative, and quantitative description of the site unsaturated zone hydrogeologic system under present as well as probable, or possible, future conditions.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. In FY 1995, the unsaturated zone infiltration study (8.3.1.2.2.1) was reconfigured and accelerated. The reconfiguration resulted in data from other studies being used to satisfy the SCP objectives of this study. However, the artificial infiltration activities were not implemented. The primary goal of the reconfigured study became defining the spatial and temporal distribution of moisture flux for the upper boundary condition for site-scale models of unsaturated zone ground-water flow and transport. In this context, the boundary condition is being developed as a conceptual and numerical model using arid-land watershed processes. The model is providing a dynamic link between infiltration flux and known climatic variability, potential climatic trends, potential changes in the surface environment (such as loss of vegetation), and sporadic but extreme meteorological events. The integration of hydrologic-process models for the surface and near-surface environments with mapped surficial-material hydrologic properties and mapped present-day net infiltration rates (as measured in the neutron-access boreholes) is resulting in a stochastic-deterministic simulation of future upper-boundary conditions, including the probability and magnitude of potential fast pathways of net infiltration.

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A surficial-materials infiltration-properties map of the Yucca Mountain area showing the spatial distribution of eight statistically significant soil units was developed, but the field and laboratory measurements used to produce the map were reduced both in number and scope from that envisioned in the SCP. The effects of the reduction on data representativeness and utility of the properties map have not yet been determined. At the end of FY 1995, moisture monitoring in the network of neutron-access boreholes was discontinued after 10 years of monitoring because additional monitoring data is no longer needed to support the long-range plan. A multiple linear regression model was developed to correlate annual shallow-infiltration estimates measured in 69 neutron-access boreholes to annual precipitation, depth to bedrock, and other hydrogeologic factors, but the series of double-ring-infiltrometer and ponding studies to determine the range and spatial variability of infiltration rates (artificial infiltration) were not conducted. Similarly, although one detailed water-balance study of Split Wash was initiated to develop and calibrate the evapotranspiration component of the infiltration model, the number and scope of such watershed-scale studies was reduced considerably. Further, the artificial-infiltration control-plot studies were never implemented. Finally, although a numerical model was developed that simulates the interaction of critical processes that result in net infiltration, the small- and large-plot rainfall-simulation tests (artificial infiltration) were not conducted; these tests were intended to validate the model with respect to temporal and spatial distribution of infiltration under both current-climatic and wetter conditions.

The monitoring of moisture flux in the neutron-access boreholes over the last 10 years has afforded an opportunity to observe natural infiltration events and precluded conducting artificial infiltration experiments. One of the objectives of the artificial infiltration experiments initially planned at the time of the SCP was to approximate the effects of potentially wetter pluvial rainfall events. As a result of several El Niño winter storm events over the last few winters (especially 1993 and 1994), unusually large precipitation events have occurred. Monitoring the vertical moisture profile following these events has given direct evidence of the expected effects of wetter climate periods in the future. These El Niño events are estimated to be analogous to the expected precipitation during wetter pluvial periods.

2. The water movement test study (8.3.1.2.2.2) has expanded considerably in scope and complexity from that outlined in the SCP. The expanded scope was intended to provide corroboration of borehole data which indicated the pore waters were on the order of hundreds of thousands of years old. Corroboration, if provided, was expected to support low-flux arguments. The SCP indicated that sampling of tuffs for chlorine-36 would focus primarily on obtaining a profile in what was then planned to be a vertical-shaft ESF. Additional chlorine-36 measurements were to be performed on samples collected after a survey of Yucca Mountain to determine areas of active percolation. Since that time, the set of targets for sampling has expanded to include (a) soil samples within the "perimeter-drift boundary" and from pits in Midway Valley, (b) drill cuttings from the last set of neutron-access holes and deep systematic drilling, unsaturated zone and north ramp geologic boreholes, (c) pore water extracted from

cores of deep unsaturated zone and north ramp geologic boreholes, (d) rain water and water from the bottom of neutron holes, (e) perched water from several deep boreholes near the ESF, (f) water samples from several deep saturated-zone holes, (g) water from springs and shallow wells in the Amargosa Valley and Death Valley, and (h) packrat middens. With the reconfiguration of the ESF into ramps and drifts, the number of samples from the ESF has increased substantially through systematic sampling along the tunnel and sampling of discrete structural features that potentially are fast-transport paths. The complexity of the study also has increased by using the chlorine-36 method to investigate the spatial frequency of fracture flow, residence times of infiltrating water, and ground-water travel times. In addition, the chlorine-36 results have been used in connection with the site-scale unsaturated-zone transport model to estimate percolation flux at the repository horizon.

3. The percolation in the unsaturated zone—surface-based study (8.3.1.2.2.3) has been reduced in scope. The SCP indicated that 17 vertical boreholes would be drilled, tested, and instrumented in support of this study, 9 of which would penetrate to just above the proposed repository horizon and 8 of which would penetrate the unsaturated zone below the proposed repository horizon. Monitoring of pneumatic pressure, temperature, and water potential was to be performed in each hole for a minimum of 3 to 5 years. Although 15 holes have been drilled and used by this study, 4 of these were drilled along the alignment of the north ramp of the ESF rather than in the feature-based locations originally planned. Of the 15 holes drilled, 8 terminated above the repository horizon and 7 penetrated to below the repository horizon. However, no deep borehole has been drilled, or excavation made, to characterize the Ghost Dance fault in the Calico Hills Formation below the repository horizon. In addition, air-injection tests to determine gas-phase permeability have been conducted in only 4 of the holes, only one of which penetrated below the repository horizon. Further, no cross-hole pneumatic or gas-tracer tests have been conducted and no additional pneumatic tests are planned. Of the 15 holes drilled, only 7 have been instrumented as planned to monitor pneumatic pressure, temperature, and water potential, while 2 holes were instrumented for pressure and temperature (Nye County), 2 for pressure only (flexible borehole liners), and 1 for vertical seismic profiling. A significant change in the study has been the increased emphasis on the effects of ESF construction on the natural gaseous-phase system. Contrary to the SCP, no boreholes have been drilled and tested on opposite sides of the Solitario Canyon fault or at the southern end of Yucca Mountain. Further, no boreholes at the crest of Yucca Mountain have been instrumented for hydrologic monitoring or for vertical seismic profiling. Finally, water-injection tests in instrumented boreholes and the Solitario Canyon horizontal borehole study have been deleted from the testing program. However, many of the objectives of the Solitario Canyon horizontal borehole study may be met by hydrologic testing in the east-west drift planned for the ESF.

Although there are no surface-based boreholes planned to intersect the Ghost Dance fault, two test alcoves off the main ESF tunnel are being constructed, and horizontal boreholes drilled from these alcoves are intended to intersect the Ghost Dance fault.

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The hydrogeologic testing intended for these boreholes would allow characterization of the hydrologic conditions in the vicinity of the fault at the repository horizon. These hydrologic conditions will then be used to constrain the unsaturated zone flow and transport models.

4. In the percolation in the unsaturated zone—exploratory studies facility study (8.3.1.2.2.4), a number of changes in testing strategy resulted from the reconfiguration of the ESF from vertical shafts to ramps and drifts. The multipurpose-borehole testing was deleted because of its association with vertical shafts and was replaced by the series of north ramp geologic holes and other boreholes. The intact-fracture and excavation-effects tests have been terminated because they would not lead to a reduction in residual uncertainty in hydrologic parameters at the site scale. Although the percolation tests on blocks of intact rock were deleted from the testing program, a reconfigured series of in situ field tests are being planned to estimate the flux of water moving downward through the repository horizon in the ESF under present-day conditions. Further, a test not anticipated in the SCP involving moisture monitoring in the ESF is under way. This test is intended to develop a water mass balance for the ESF and to determine how much naturally occurring water is being removed from the ESF by the ventilation system. The in situ testing for the bulk-permeability test has been combined with the radial-boreholes and major-faults tests, both of which are ongoing. The modeling portion of the bulk-permeability test is being accomplished under Study 8.3.1.2.2.8 (Fluid Flow in Unsaturated Fractured Rock). As a discrete test, testing of the Calico Hills nonwelded hydrogeologic unit (CHn) in the ESF was deleted from the study plan in Revision 9 of the Site Characterization Program Baseline (DOE, 1995g) (see Appendix H). Testing in the CHn may be conducted as part of other future ESF testing activities.
5. No diffusion tests have been conducted in the ESF (Study 8.3.1.2.2.5), and plans to conduct such tests have been suspended indefinitely. Natural radioisotopes have been encountered in samples collected at several locations from the ESF and surface-based boreholes. The occurrence of these naturally occurring (albeit anthropogenically enhanced) tracers will continue to be used in conjunction with laboratory testing of matrix diffusion processes and parameters to define the role of matrix diffusion in the unsaturated zone radionuclide transport model. Also, tracer testing in the saturated zone at the C-hole complex will provide additional information, at the scale of several tens of meters, about the role of matrix diffusion in the tuffaceous rocks at Yucca Mountain.
6. Although the gaseous-phase movement study (8.3.1.2.2.6) has collected and used data from about a dozen more boreholes than was expected, the scope of work planned for key locations and boreholes has been reduced. For example, neither the two vertical boreholes planned to straddle the Solitario Canyon fault nor the horizontal borehole to penetrate it were drilled. Also, the cross-hole tracer tests planned for the USW UZ#9 borehole complex have not been conducted because this cluster of boreholes has been deleted from the testing program. Further, the extensive sampling of boreholes for

chlorofluorocarbons to determine residence time of gas in the Tiva Canyon unit and to investigate possible breaches in the Paintbrush nonwelded hydrogeologic unit was not conducted. One impact of reducing the scope of work for this study is that barometric pumping, which is potentially an important mechanism for water vapor and heat removal, may not yet have been effectively evaluated. Sensitivity analyses will be necessary to determine the extent to which barometric pumping must be characterized for performance assessment purposes.

A significant change from the original study strategy has been the use of the effects of ESF construction on the gaseous-phase system to estimate pneumatic properties of the unsaturated zone. This was new work, identified since the SCP was issued. The work was done to take advantage of the opportunity to use barometric responses to estimate large-scale pneumatic diffusivity in the ESF. Specifically, a numerical gas-flow model of the ESF north ramp was constructed to simulate the progressive effects of excavating the north ramp as detected in nearby surface-based boreholes (Patterson et al., in prep.) A parameter-estimation technique was used to determine horizontal and vertical permeabilities of the Topopah Spring Tuff (see Section 3.1.10 of this progress report). Although this preliminary, three-dimensional gas-phase modeling of the ESF north ramp area was done for this study, all remaining site-scale, gas-phase modeling will be done under Study 8.3.1.2.2.9.

An additional activity was added to this study involving use of a water-vapor RAMAN-LIDAR system to investigate preferred pneumatic pathways that have surficial expression. This activity, however, has not progressed beyond the prototype stage and has been suspended indefinitely.

7. In the unsaturated zone hydrochemistry study (8.3.1.2.2.7), pore water has been extracted for hydrochemical and isotopic analysis from the cores of 9 of the 15 boreholes drilled to support deep unsaturated zone studies (see item 3 above). Detailed, time-series gas-composition and isotopic-content data has been collected for one deep borehole, which is north of the repository and may or may not be representative of conditions in the potential repository area. Gas samples have been collected from 8 other boreholes, and in two instances the sampling was very limited. Further, gas samples have been collected from below the Calico Hills Formation in one borehole. Overall, although the basic objectives and strategy for this study have not changed, inferences and conclusions regarding fluid movement have had to be based on fewer data from fewer locations in the vicinity of Yucca Mountain. Significant additional information on naturally occurring radioisotopes has been collected from the ESF. These data have provided increased confidence in the unsaturated zone flow and transport models. These data from the ESF combined with the borehole hydrochemical and isotopic data have been used to constrain these models. Assessment of the sufficiency of the data will be made after the data have been analyzed and a reaction-mass balance model has been developed.

8. Because of significant changes in the ESF testing strategy (see item 4 above), the flow in unsaturated fractured rock study (8.3.1.2.2.8) has de-emphasized the development of conceptual and numerical models solely for design and interpretation of small-scale ESF tests. Instead, the study has concentrated on using all data available from the ESF to construct representative fracture-flow models at about the drift scale. These models, particularly of the Topopah Spring welded unit, are expected to provide significant insight into the possible spatial distribution and magnitude of fracture flow that might occur into drifts of the proposed repository. In addition, the study has developed a series of modeling approaches for small-scale flow phenomena that can be applied directly to the unsaturated zone site-scale model. These include fracture/matrix interaction modules, a hysteresis model, and an equivalent for unsaturated fracture-network models. These approaches and models provide the theoretical and applied basis for evaluating of various complex processes within the site-scale model.
9. The site unsaturated-zone modeling and synthesis study (8.3.1.2.2.9) has exceeded expectations for simulation of the site-scale unsaturated zone system. This has occurred, in part, because of significant advances in the numerical code and computer technology used in the modeling effort. In addition, the construction of the ESF ramp-and-drift configuration during the time that the site-scale model was being developed has afforded an unexpected opportunity to calibrate the gaseous-phase portion of the model. Although it has been necessary to develop and calibrate the model with data from fewer surface-based boreholes than originally expected, data from instrumented boreholes documenting the effects of ESF construction on the gaseous-phase system has made possible enhanced, large-scale, transient-state modeling of gas-pressure propagation through the mountain. These data have led not only to the enhanced simulation of the gaseous phase but also to improved understanding and representation of fracture and fault diffusivities and permeabilities in the site-scale model. Further, using temperature-gradient and heat-flow data for the unsaturated zone has led to an enhancement of the ability of the model to simulate and predict moisture flow. The non-uniqueness of model calibration based on pressure-response alone is recognized, and the model will need to be further constrained by information that explains pneumatic diffusivity in terms of gas-transport pathways. As calibration of the model continues, determinations of whether sufficient data have been collected to validate the model are being made using sensitivity analysis. These determinations will consist of trade-off analyses to prioritize information needed and/or useful to reduce uncertainties in the model in significant and quantifiable ways.

A.1.1.3 Studies to provide a description of the saturated zone hydrologic system at the site (SCP Investigation 8.3.1.2.3)

Background and SCP Plans. The objective of this investigation was to develop a model of the saturated zone hydrologic system of Yucca Mountain that will help assess the suitability of the site to contain and isolate waste. Developing this model requires an understanding of ground-water flow. This understanding will be provided through studies focusing on the

determination of boundary conditions imposed by structure, recharge, and discharge; hydraulic gradients in three dimensions; and bulk aquifer properties of units. Modeling activities will use the resulting information to calculate ground-water flow paths, fluxes, and velocities within the saturated zone. This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.2.3.1 (characterization of the site saturated zone ground-water flow system): This study was to (a) determine the hydrogeologic nature of the Solitario Canyon fault in the saturated zone; (b) refine the spatial and temporal distribution of the potentiometric surface at the site to determine hydraulic gradients and ground-water flow magnitudes and directions; (c) analyze water-level fluctuations to determine their causes and to estimate formation properties; (d) analyze previously completed single- and multiple-well hydraulic-stress tests conducted in the C-holes to determine type of flow, hydraulic boundaries, and bulk hydraulic properties; (e) conduct multiple-well interference testing in the C-holes to determine hydraulic properties, the appropriateness of anisotropic porous-media or fracture-network models, and the appropriateness of single-well or multiple-well tests; (f) conduct single- and multiple-well conservative tracer tests at the C-holes and throughout the site to determine transport properties; and (g) conduct reactive tracer tests in the C-holes and throughout the site to determine properties of the geologic media that will affect retardation of radionuclides in the saturated zone.
2. Study 8.3.1.2.3.2 (characterization of the saturated zone hydrochemistry): This study was to (a) describe the spatial variations in chemical composition of saturated zone ground waters in the regional and site areas through analysis of representative water samples collected from wells and springs; (b) describe the chemical and isotopic composition of the upper part of the saturated zone through analysis of representative water samples collected from the upper 100 m of the saturated zone; (c) conduct geochemical modeling to identify chemical and physical processes that influence ground-water chemistry; and (d) aid in the identification and quantification of ground-water travel times, climatic conditions during periods of recharge, and fluxes to and from the saturated zone by analyzing the chemical and isotopic compositions of interstitial-water and gas samples collected from immediately above the water table.
3. Study 8.3.1.2.3.3 (saturated zone hydrologic system synthesis and modeling): This study was to (a) synthesize available data into a conceptual model and make a qualitative analysis of how the site saturated zone hydrogeologic system was functioning; (b) develop fracture-network models for simulating ground-water flow and conservative solute transport and relate results of hydraulic and conservative-tracer tests in wells to fracture-network characteristics; and (c) develop a comprehensive site-scale model of ground-water flow and transport to simulate ground-water flow direction and magnitude for input into travel-time calculations and evaluate the appropriateness of the porous-media and fracture-network concepts.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection.

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The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. In the site saturated zone ground-water flow system study (8.3.1.2.3.1), the study of the Solitario Canyon fault in the saturated zone has not been conducted and is not included in the long-range plan. The Solitario Canyon fault is not considered as critical to predicting movement of radionuclides in the saturated zone as are hydrogeologic features and conditions downgradient from the repository area. Although 14 of the planned 22 water table boreholes were drilled in the early 1980s, none of the additional 8 water table holes have been drilled, including the two for the Solitario Canyon fault study and the two to investigate the large hydraulic gradient. Although some hydraulic tests have been conducted in borehole USW G-2, these tests resulted in no new major understanding and the nature and cause of the large hydraulic gradient remain unresolved. One of the water table holes designed to investigate the large hydraulic gradient may or may not be completed. If the hole is not completed, the uncertainty in the estimate of the inflow boundary condition for the site-scale model will be less constrained.

Although the C-holes multiple-well interference and tracer tests are being conducted mostly as planned, not as many of the high-producing flow zones will be tested as planned, and probably none of the low-producing zones will be tested. In addition, the sequencing of testing has been modified in that hydraulic, conservative-tracer, and reactive-tracer tests are being conducted sequentially in a single flow zone before conducting any tests in the next flow zone. Although single-well hydraulic tests have been conducted in two water table holes (USW WT-10 and UE-25 WT#12), the results are of limited value. Therefore, no other single-well hydraulic or tracer tests are planned for two reasons: (1) storativity data were not obtainable from the tests, and (2) well-bore losses imparted additional uncertainties to the test results. Instead, a second multiple-well test site is planned along a flow path south of the repository footprint. There hydraulic and tracer tests will be conducted to determine hydrologic properties and to measure the reduction in the concentration of solutes as they move through the saturated zone. The adequacy of the data to support performance assessment may be evaluated using sensitivity analyses.

2. In the saturated zone hydrochemistry study (8.3.1.2.3.2), the SCP called for intensive water and gas sampling from discrete intervals of 22 water table holes, 14 existing and 8 new holes. Hydrochemical testing was to include the clean out of all the existing water table holes, extraction and analysis of interstitial water from cores of the new holes, and multielement geochemical analyses of selected samples. Although a few mixed-interval samples have been collected from two water table holes, the C-holes, and USW G-2, the site saturated zone hydrochemistry study remains largely unimplemented. Subsequent to the SCP, a plan was devised for in situ determinations of pH, Eh, and temperature in all 22 water table holes using a sophisticated downhole hydrochemical tool. However, this plan was abandoned because of its high cost, uncertain potential for increasing knowledge, and the need to support critical saturated zone modeling efforts. Although a limited number of water samples have been collected for chemical and isotopic analyses from springs during the regional study near Death Valley, the regional hydrochemistry study also remains largely unimplemented. Regional hydrogeochemical information has been collected by other programs along the likely flow paths of regional ground-water flow. The regional data, combined with the limited data collected under this study, can be used to enhance the confidence in the regional ground-water flow model. However, the geochemical "signatures" of greatest interest occur over large scales and are more indicative of general mixing of regional ground waters than of any site-specific flow paths. The geochemical "signatures" of interest are stable isotope ratios and major dissolved ions along flow paths. Geochemical reaction and mass-balance models should be consistent with hydrologic and hydrochemical data for self-consistent interpretations of water sources, mixing relationships, and geochemical reactions along hydrologic flow paths.

3. In the site saturated zone hydrologic system synthesis and modeling study (8.3.1.2.3.3), construction and calibration of a site-scale, porous-media-equivalent flow model is proceeding generally as planned. However, because of the application of sophisticated Geographic Information System and geologic-modeling techniques, the geologic framework model on which the flow model is based may be more rigorous and detailed than was envisioned when the SCP was issued. Nevertheless, although not yet calibrated, the final saturated zone, site-scale model will contain significant uncertainty for several reasons: (a) limited field tests have been completed to characterize the large-scale anisotropy because of a sparsity of hydraulic-test locations to serve as control points for model calibration; (b) uncertainty persists about the cause of the large hydraulic gradient; (c) uncertainty persists about fluxes at the northern model boundary because no potentiometric data are available in the Timber Mountain area to calibrate the regional model from which boundary fluxes are derived for the site-scale model; (d) hard data is sparse on the geometry and hydraulic properties of the Paleozoic carbonate aquifer underlying Yucca Mountain; and (e) high quality chemical and isotopic data from the saturated zone are not sufficient to corroborate flow patterns.

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The degree to which these uncertainties in the saturated zone flow model affect the relevant output from the model used in total system performance assessment will be ascertained by a range of sensitivity analyses. These analyses are planned as part of the abstraction of this model in the total system performance assessment. Although uncertainties are expected to remain, the impact of these uncertainties on total system performance assessment will be evaluated.

Although "generic" fracture-network-modeling techniques have been developed, a fracture-network model of the C-hole complex has not yet been developed because the extensive data that would have been required exceeded the data that could be collected. The need to develop a fracture network model will be determined by performance assessment and sensitivity analyses.

A.1.2 Geochemistry Program (SCP Section 8.3.1.3)

The geochemistry program was intended to characterize and evaluate the effectiveness of the geochemical "barriers" that are expected to inhibit the transport of radionuclides away from the potential repository. The program of geochemical testing described in the SCP concerned characterizing those areas of the site that lie beyond the "altered zone" (see Section A.1.15 of this appendix). The major purpose of the geochemistry program was to quantify the radionuclide retardation factor. This factor was expected to be greater than one, and values greater than one were expected to provide added confidence to the calculations of transport to the accessible environment based on advective and dispersive transport calculations.

A.1.2.1 Studies to provide information on water chemistry within the potential emplacement horizon and along potential flow paths (SCP Investigation 8.3.1.3.1)

Background and SCP Plans. The objectives of this investigation were to provide a ground-water chemistry model that would explain the present ground-water composition as a result of interactions of the ground water with minerals and be able to predict future variations in ground-water chemistry (under anticipated and unanticipated conditions) that would alter radionuclide flux through the saturated and unsaturated zone. This investigation included one study developed to accomplish the following:

Study 8.3.1.3.1.1 (ground-water chemistry modeling): This study was to develop pre- and postemplacement ground-water chemistry models that would integrate the unsaturated and saturated zone data with the processes of water infiltration, water flow, and mineralogic changes to develop a mechanistic description of the current and future ground-water chemistry. The study was also intended to consider changes in infiltration as influenced by climatic conditions; long-term mineralogic changes, particularly those influenced by the thermal pulse from emplaced waste; and changes in the material properties caused by the emplaced waste, or possible igneous activity.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

In the ground-water chemistry modeling study (8.3.1.3.1.1), the number of laboratory experiments on water-rock interaction has been decreased, and uncertainty remains about the quantitative models of the processes that control water chemistry in the saturated and unsaturated zones. Uncertainties involve the rate and manner in which volcanic glass is altered when it comes in contact with different water compositions, which can strongly influence pH and the concentrations of other constituents in solution. Information has been provided to studies of radionuclide retardation and transport. Additional information on the solid phases involved in the alteration of volcanic glass would be needed to develop detailed deterministic models of ground-water chemistry, if such models are determined to be necessary. The extent to which natural variability and model uncertainty affect radionuclide transport will be bounded in the total system performance assessments.

A.1.2.2 Studies to provide information on mineralogy, petrology, and rock chemistry within the potential emplacement horizon and along potential flow paths (SCP Investigation 8.3.1.3.2)

Background and SCP Plans. The purpose of this investigation was to provide the baseline set of data and a basic understanding of the natural environment in which geochemical and other processes interact. The objectives of this investigation were to determine the three-dimensional distribution of mineral types, compositions, and abundances in rocks beyond the host rock that provide pathways to the accessible environment; determine the timing, temperatures, and hydrologic conditions of past alteration at Yucca Mountain; study experimentally the dehydration of smectite, zeolite, and glass; and use the results to develop descriptive and predictive models of mineral distributions along potential pathways to the accessible environment. This investigation includes two studies developed to accomplish the following.

1. Study 8.3.1.3.2.1 (mineralogy, petrology, and chemistry of transport pathways): This study was to (a) determine the petrologic variability within the devitrified Topopah

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Spring Tuff at Yucca Mountain and define the stratigraphic distribution of variability; (b) determine the three-dimensional distribution chemistry and the total abundance of all major rock-matrix minerals, between the host rock and the accessible environment; and (c) determine the distributions of minerals within fractures at Yucca Mountain.

2. Study 8.3.1.3.2.2 (history of mineralogy and geochemical alteration at Yucca Mountain): This study was to (a) determine past temperatures from alteration mineral assemblages as a means to estimate the long-term thermal stabilities of important sorptive phases, such as clinoptilolite, and of the silica polymorphs that can influence water composition, precipitation, and the stabilities of other silicate minerals; and (b) determine how minerals and glasses in the rocks at Yucca Mountain will dehydrate and transform under expected thermal loads and investigate the ability of zeolites and smectites to rehydrate after the peak in temperature.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. In the mineralogy, petrology, and chemistry of transport pathways study (8.3.1.3.2.1), the textural features within the devitrified Topopah Spring Tuff are no longer being quantified as a guide to determining variability within the potential host rock. The method was cumbersome and prone to variability between operators conducting the activity. However, quantitative x-ray diffraction and chemical data are still being obtained. The technique of microautoradiography has been added to both the determination of mineral distributions between the host rock and the accessible environment and the work on fracture mineralogy. This addition has been made to provide the needed detailed information on partitioning between minerals in specific rock samples of retardation potential for radionuclides, both for tuff matrix samples and for fracture samples.
2. In the history of mineralogic and geochemical alteration of Yucca Mountain study (8.3.1.3.2.2), the basic objectives have not changed, but there is now greater emphasis on determining the interrelationship between alteration and hydrology. A relative chronology of alteration has been established, and the study is focused on some of the

less well understood alteration, not explicitly identified in the SCP, but responsible for the distribution of existing hydrologic properties, particularly in the Paintbrush nonwelded hydrogeologic unit. The subhorizontal tunnel design of the ESF has provided greater underground exposure of this unit than the vertical shaft design referenced in the SCP. The role of analytical geochronology has been less than originally planned because apparent ages determined by exploratory potassium-argon studies of zeolites are ambiguous. Similarly, the use of electron spin resonance dating has been minimal for lack of an appropriate source of analytical services, but this technique may yet be used to confirm the timing of mineral deposition along groundwater flow paths. Plans for petrofabric studies of zeolitic tuffs below the potential repository horizon, predicated on the availability of large oriented-block samples from an underground exploratory facility, had to be adapted to the use of drill core samples. Studies of the smaller samples revealed limited evidence for the channelization of fluid flow in partially zeolitized tuffs, and the techniques developed for these studies will be available if large samples are obtained in the future.

Heating studies of mineral and glass dehydration and transformation have proceeded largely as described in the SCP. Smectite, zeolites, and glasses are being studied, but few data have been collected for manganese minerals. The natural manganese minerals at Yucca Mountain have highly complex and variable chemical compositions and occur as intricate intergrowths of more than one mineral. Efforts to date have emphasized studies of the volumetrically more abundant clays and zeolites, yielding results that can be incorporated into numerical models of site thermal behavior and water budget. Planned experiments to heat minerals in a steam environment could not be maintained on a long-term basis with existing laboratory apparatus. The heating tests will be done by Project participants having more suitable equipment.

A.1.2.3 Studies to provide information required on stability of minerals and glasses (SCP Investigation 8.3.1.3.3)

Background and SCP Plans. The goal of this investigation was to determine the stability of minerals and glasses along the flow paths to the accessible environment to assess impacts of waste emplacement on mineral stability and the resulting effect on radionuclide retardation. The objectives of this investigation included testing the capabilities of the EQ3/6 geochemical code, improving the reliability of long-term predictions regarding hydrothermal rock alteration in devitrified welded ash flow tuff, and improving the understanding of the origin of the alteration mineral assemblages found in Yucca Mountain; investigating the kinetics of glass and silica polymorph transitions and their relationships to aqueous silica activity, and providing thermodynamic data for clinoptilolite/heulandite and albite and analcime; and developing a conceptual model of mineral evolution. This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.3.3.1 (natural analog of hydrothermal systems in tuff): This study was to improve the reliability of long-term predictions regarding hydrothermal rock alteration

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in devitrified welded ash-flow tuff using studies of occurrences of natural analog hydrothermal systems in tuffs.

2. Study 8.3.1.3.3.2 (kinetics and thermodynamics of mineral evolution): This study was to (a) predict the rates of possible transformation of silica polymorphs in Yucca Mountain and the effects such transformations would have on aqueous silica activity; (b) determine the end-member free energies from solubility measurements of clinoptilolite-heulandite, albite, and analcime; and (c) describe the thermo-dynamics of the clinoptilolite-heulandite and analcime solid solutions in support of the development of the mineral stability model.
3. Study 8.3.1.3.3.3 (conceptual model of mineral evolution): This study was to produce a conceptual model to explain the observed distributions of minerals in Yucca Mountain, address the general chemical evolution of vitric tuffs, and predict future mineral evolution in the mountain caused by both natural processes and as a result of a repository emplacement.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. The natural analog of hydrothermal systems in tuff study (8.3.1.3.3.1) has not been initiated as described in the SCP. The potential performance-related implications of possible hydrothermal alteration of tuffaceous rocks would be on the flow and transport characteristics along the likely paths of radionuclide transport between the potential repository and the water table. The dominant change would be on the retardation characteristics of the mineral assemblages. Initial indications are that such alterations cause insignificant changes in the retardation coefficient that are well within the expected natural variability observed in the characterization program (Bish et al., in prep.). Given that the changes are within the bounds of natural variability, the need to confidently determine the reliability of any particular water-rock interaction model using natural analogs is minimized.

2. The kinetics and thermodynamics of mineral evolution study (8.3.1.3.3.2) was combined with the study on conceptual model of mineral evolution (previously 8.3.1.3.3.3). These studies were combined to integrate the experimental and modeling aspects of mineral evolution and to create the necessary ties between experiment and performance models. There is a feedback between these two studies, with kinetics and thermodynamics experimental results providing input into the conceptual model, which subsequently influences the experimental program. Efforts to investigate glass reactions are no longer planned because these studies are now parts of Studies 8.3.1.20.1.1 (altered zone characterization) and 8.3.4.2.4.1 (characterize chemical and mineralogical changes in the postemplacement environment). Studies on the dissolution and precipitation kinetics for zeolites have been expanded to include an experimental component because insufficient site-specific data were available in the literature. These studies now include clinoptilolite, mordenite, illite/smectite, and analcime. Solubility studies of zeolite free energies have been augmented to include mordenite, and these studies will no longer consider albite because sufficient literature data exist. The data reduction codes listed in the SCP under this activity will not be used; instead Yucca Mountain Site Characterization Office (YMSCO)-approved codes such as EQ3/6 will be used. Efforts to describe the thermodynamics of zeolite equilibria have been expanded to include mordenite and other minor zeolites at Yucca Mountain such as erionite, chabazite, and phillipsite.
3. The study on conceptual model of mineral evolution (previously 8.3.1.3.3.3) was combined with the kinetics and thermodynamics of mineral evolution study (8.3.1.3.3.2). See description under item 2 above.

A.1.2.4 Studies to provide the information required on radionuclide retardation by sorption processes along flow paths to the accessible environment (SCP Investigation 8.3.1.3.4)

Background and SCP Plans. The purpose of this investigation was to obtain data on the sorption behavior of key radionuclides (americium, carbon, cesium, curium, iodine, neptunium, plutonium, strontium, technetium, uranium, and zirconium). The objectives of this investigation were to obtain sorption coefficients for key radionuclides as functions of the composition of ground water, substrate compositions and structures, acidity (pH), reduction-oxidation potential (Eh), and other parameters; evaluate effects of microorganisms on the movement of radioactive waste, and determine if microbial activities play a role significant enough to be included in performance calculations; and model the sorption experiments on rocks and minerals representing the proposed repository block and derive a capability to predict sorption coefficients for key radionuclides under water-rock conditions not included within the experimental program. This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.3.4.1 (batch sorption studies): This study was to (a) determine sorption coefficients for radionuclides on tuffs of the Calico Hills Formation zeolitic and vitric units, on devitrified tuffs, and on pure minerals representative of the minerals present

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in the rock and fractures of the repository block; (b) characterize the dependence of sorption coefficients upon the concentration of the element being sorbed by developing isotherms for the radionuclides; (c) measure sorption coefficients as functions of ground-water compositions anticipated along potential travel paths and determine if the values of K_d were above specified values; (d) determine if sorption of important radionuclides occurs along particulates or colloids that may be present in ground waters along potential transport pathways; and (e) produce statistical correlations and error estimates.

2. Study 8.3.1.3.4.2 (biological sorption and transport): This study was to quantify the locations and characteristics of past and potential future organic materials used at the site and their susceptibilities to microbiological degradation by determining the growth of microorganisms in fluids such as drilling fluids, evaluating the influence of microorganisms on the movement of actinides by mechanisms such as colloidal agglomeration and chelation, and determining the binding constants of microorganisms to actinides.
3. Study 8.3.1.3.4.3 (development of sorption models): This study was to (a) model the sorption experiments on rocks and minerals representing the proposed repository block and to derive a capability to predict sorption coefficients for key radionuclides under water-rock conditions not included within the experimental program; and (b) develop the best possible capability for predicting sorption coefficients for key radionuclides in the proposed repository block using the available data.

Changes and Status. No significant changes in these studies have been made since the SCP was issued.

1. The batch sorption study (8.3.1.3.4.1) is about three-quarters complete, and the work is generally consistent with the description in the SCP. Work remains to complete the data set for plutonium. This work on plutonium has been complicated by the multiple oxidation states of plutonium and by difficulties in obtaining ground waters with different compositions. However, the focus of the study is expected to begin shifting to synthesis and integration of the sorption data to support identification of optimal sorption models that will be used in performance assessment.
2. The biological sorption and transport study (8.3.1.3.4.2) is fairly mature. Since the SCP was issued, study progress and developments in the field of subsurface microbiology have been used to change the focus of the study. Changes to the study, as described in the SCP, are discussed in detail in the study plan, but no substantive changes to the study have been made since the study plan was approved in 1993. Most of the changes identified in the study plan are simple reorganizations of the SCP tasks. However, one study (v-max and actinide speciation) has been deleted because the investigation was determined to be beyond the needs of the program. Remaining work includes support for the development of process models for site-scale unsaturated zone transport and waste package degradation, site-scale saturated zone transport, and

portions of the waste containment and isolation strategy that utilize container corrosion estimates and actinide concentrations.

3. The development of sorption models study (8.3.1.3.4.3) remains relatively incomplete because of resource constraints over the past several years. The work that has been accomplished has generally progressed consistently with the description in the SCP. At this time, it appears that it may be necessary to resolve three remaining technical questions to produce defensible sorption models for performance assessment. These questions are: (a) oxidation state of plutonium sorbed into tuffs, (b) speciation of neptunium sorbed onto zeolitic tuffs, with emphasis on the roles of clinoptilolite and clay, and (c) speciation of neptunium sorbed onto fracture coatings such as mineral oxides and calcite. The focus of this study is expected to shift from sorption model development to evaluation of the mechanistic sorption models, and identification and selection of the optimal sorption model for use in performance assessment.

A.1.2.5 Studies to provide the information required on radionuclide retardation by precipitation processes along flow paths to the accessible environment (SCP Investigation 8.3.1.3.5)

Background and SCP Plans. The objective of this investigation was to collect data needed to evaluate potential radionuclide retardation by precipitation processes. Data about dissolved species concentration limits were intended to provide information on solubility or concentration limits for dissolved species of important waste elements under conditions that were characteristic of the repository and along flow paths to the accessible environment. Data about colloid behavior would be used to determine the stability of waste element colloids under expected site-specific conditions that might be encountered at the repository or along flow paths to the accessible environment. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.3.5.1 (dissolved species concentration limits): This study was to (a) specify the conditions under which solubility experiments would be performed and then measure solubilities or concentration limits of important waste elements under these conditions; (b) identify important aqueous species of waste elements under conditions specified and determine the formation constants for those species; and (c) develop the thermodynamic models and data needed to calculate waste element solubilities over a range of conditions expected at the site.
2. Study 8.3.1.3.5.2 (colloid behavior): This study was to (a) determine the formation and stability of waste element colloids, particularly plutonium and americium; (b) the study conditions for colloid formation, stability, and break up include pH, reduction-oxidation state, temperature, and concentration of the element; (c) determine the effect of these conditions on colloid size, density, composition, charge, and chemical reactivity; and (d) develop models and model parameters to calculate natural colloid

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concentrations and stability and describe the disposition of the waste element species as the colloids break up.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. The dissolved-species concentration limits study (8.3.1.3.5.1) has essentially remained unchanged since the SCP was issued. Emphasis has been placed on identifying the solubility-limiting solids and oxidation states and on developing a thermodynamic data base for neptunium and plutonium. The strategy for sorption studies and subsequent performance assessments generally supported an emphasis on neptunium and plutonium as key radionuclides. The interest in investigating oxidation states resulted from the realization that these elements are much less soluble under reducing conditions.
2. In the colloid behavior study (8.3.1.3.5.2), a letter report on plutonium (IV) colloids was written to document the literature data base (Clark, 1994). All other work has been deferred because it is not needed to support the long-range plan. Uncertainties in colloid formation, stability, and mobility will be addressed as part of the total system performance assessment. Reasonable ranges in naturally occurring colloid and radiocolloid properties will be derived from literature surveys and other direct and indirect sources.

A.1.2.6 Studies to provide the information required on radionuclide retardation by dispersive, diffusive, and advective transport processes along flow paths to the accessible environment (SCP Investigation 8.3.1.3.6)

Background and SCP Plans. The objective of this investigation was to experimentally determine the rate of movement and effective retardation of radionuclides by dispersive, diffusive, and advective processes. The dynamic transport column experiments were intended to measure the breakthrough or elution curves for tracers through tuff columns. The diffusion study was intended to measure the diffusivity and kinetics of adsorption in a purely diffusive system

(i.e., no advection) using beakers fabricated from tuff wafers and rock slabs. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.3.6.1 (dynamic transport column experiments): This study was to (a) measure the rate of movement of radionuclides through crushed tuff columns relative to tritiated water and other well-defined chemical species or colloids; (b) determine the elution rate of radionuclides as a function of water velocity for crushed tuff columns (homogeneous system), for solid rock columns (heterogeneous system), and for pure mineral samples; (c) measure the relative migration rate of radionuclides through partially unsaturated rock columns; (d) measure the transport and diffusion of radionuclides through naturally fractured tuff; and (e) quantify the filtration of colloids and particulates by the tuff as a function of particle or pore size.
2. Study 8.3.1.3.6.2 (diffusion): This study was to (a) measure the uptake of radionuclides by rock beakers as a function of time; (b) measure the diffusion of radionuclides in a purely diffusive system (i.e., no advection); and (c) determine the distribution of radioactivity in the unsaturated tuff matrix using an unsaturated tuff block of the Topopah Spring Tuff or Calico Hills Formation.

Changes and Status. There have been no significant changes in these studies since the SCP was issued.

1. The dynamic transport column experiments study (8.3.1.3.6.1) is about three-quarters complete. Questions remain about the validity of using batch sorption distribution coefficients (K_d s) for unsaturated zone transport calculations. An encouraging, but limited set of data, including data from experiments with uranium and selenium, indicate that K_d s can be used to make conservative predictions of radionuclide transport through unsaturated tuff.
2. The diffusion study (8.3.1.3.6.2) is about four-fifths complete. Diffusion coefficients have been determined for a fairly comprehensive set of radionuclides, tuff types, and water compositions. Diffusion as a function of saturation in tuffs remains to be determined, and additional data about diffusion along fractures is also required.

A.1.2.7 Studies to provide the information required on radionuclide retardation by all processes along flow paths to the accessible environment (SCP Investigation 8.3.1.3.7)

Background and SCP Plans. The objectives of this investigation were (a) to provide a baseline set of input data from geochemistry, mineralogy-petrology, hydrology, and other studies needed for the integrated radionuclide transport calculations; and (b) to outline the strategy that would be used to demonstrate the validity of the laboratory generated geochemical data and the validity of transport calculations using that data. This investigation included two studies developed to accomplish the following:

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1. Study 8.3.1.3.7.1 (retardation sensitivity analysis): This study was to (a) analyze the processes that may affect transport, including geochemical and physical processes, particulate transport, heat-load effects, and coupled phenomena; (b) develop, using this analysis, laboratory experiments to examine the physical and geochemical processes affecting radionuclide transport and other diffusion experiments; (c) correlate and validate results obtained from laboratory, ESF, and field experiments with transport calculations; (d) perform calculations of radionuclide transport from the repository to the accessible environment using, as a basis, an integrated conceptual geochemical-geophysical model of Yucca Mountain; and (e) verify computer codes and validate the models used in this study to identify important contributors to uncertainties in the retardation calculations (sensitivity analyses).
2. Study 8.3.1.3.7.2 (demonstration of the applicability of laboratory data to repository transport calculations): This study was to outline the strategy that would be used to demonstrate the validity of the laboratory-generated geochemical data and of transport calculations using that data including modeling and a combination of large-scale laboratory experiments, field studies, consideration of natural analogs, information from processes in the soil zone, and peer review.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued, and there have been no significant changes in the studies. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. The retardation sensitivity analysis study (8.3.1.3.7.1) has proceeded generally as described in the SCP.
2. The study to demonstrate applicability of laboratory data (8.3.1.3.7.2) has not evolved beyond the planning stages because insufficient hydrologic information has been developed to determine the location suitable for such a test. However, the C-hole tracer tests include a suite of tracers which, because of their properties, would be expected to help quantify fracture flow and adsorption in the saturated zone. The results of the C-hole tests are needed to evaluate a variety of models ranging from analytical (close-form) solutions to three-dimensional numerical models. The modeling exercise using the C-hole data is expected to provide important information

needed to determine the level of complexity needed in the site-scale model. For example, dual permeability models may be required to explain the C-hole data.

A.1.2.8 Studies to provide the information required on retardation of gaseous radionuclides along flow paths to the accessible environment (SCP Investigation 8.3.1.3.8)

Background and SCP Plans. The purpose of the investigation was to supply input data for calculations of gaseous radionuclide transport from the repository to the accessible environment at the Yucca Mountain site. The objectives of this investigation included: (a) calculating the rates of transport of gaseous radionuclide species between the repository and the accessible environment considering the various driving forces and retardation mechanisms that may exist, and (b) experimentally verifying existing models of gaseous radionuclide transport and retardation that were used to assess radionuclide release to the environment. This investigation included one study developed to accomplish the following:

Study 8.3.1.3.8.1 (gaseous radionuclide transport calculations and measurements): This study was to (a) determine the manner in which gaseous species were transported in the unsaturated zone and calculate transport rates without retardation; (b) identify the retardation mechanisms that can affect the transport of gaseous species through the unsaturated zone and model these processes so that the effects on transport rates can be evaluated; and (c) measure experimentally gas transport rates under typical unsaturated zone conditions to verify calculational models of gas transport and retardation if they exist.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

This investigation has not been funded and gas-transport pathways have not been delineated nor their transport properties characterized because this information is not essential to support the long-range plan.

A.1.3 Rock Characteristics Program (SCP Section 8.3.1.4)

The rock characteristics program was intended to provide the information needed to develop a three-dimensional model of the physical properties of the rocks at the Yucca Mountain site. That is, the program would determine the geometries associated with the various material properties of the rocks at the site. The purpose of the three-dimensional model was to provide a computer-based representation of the physical properties of the rocks at the site. The model was intended to include data defining the distribution of parameters (physical properties) within specified property-dependent units. The model data were also intended to provide input for numerical computer analyses that involve hydrologic, thermal, thermomechanical, and geochemical processes.

The three-dimensional physical properties model was intended to be a representation of the Yucca Mountain repository site containing various kinds of data on assorted geologic, geohydrologic, thermal, mechanical, and geochemical properties. One of the purposes of the model was to allow predictions of how a physical property changes spatially within and across the boundaries of the model. The relevant model boundaries would represent distinct changes in the property of interest.

The investigations included in the rock characteristics program are summarized in the following sections.

A.1.3.1 Development of an Integrated Drilling Program and Integration of Geophysical Activities (SCP Investigation 8.3.1.4.1)

Background and SCP Plans. The objective of this investigation was to provide a mechanism for the overall integration of the surface-based activities to be conducted during site characterization. The SCP and early study plan drilling programs provided for drilling the following holes: (a) 12 systematic drilling program boreholes supporting the rock properties investigations; (b) 25 additional unsaturated zone neutron access boreholes for study of shallow infiltration in the site area; (c) 17 new unsaturated zone boreholes supporting the characterization of the deeper portion of the unsaturated zone; (d) at least 5 deep water table holes, and a southern tracer complex of 3 boreholes to test the saturated zone; (e) 3 volcanic (V) boreholes; and (f) 3 additional deep geologic (G) boreholes. This ambitious program is described in the Catalog of Planned Boreholes (CRWMS M&O, 1993a).

The geophysical integration activity was intended to review and evaluate planned geophysical surveys for (a) consistency with the results from past surveys, (b) direct or supportive uses of the data for licensing, (c) the likelihood that useful data would be generated, (d) the need for the planned effort with respect to alternate methods for obtaining the data, and (e) scheduling with respect to other studies and the overall priorities for site characterization.

1. Activity 8.3.1.4.1.1 (development of an integrated drilling program): This activity was to (a) ensure data collected during surface-based testing activities were representative

of phenomena and structural characteristics; (b) integrate and prioritize surface-based activities; and (c) maintain a system of technical element baseline approval and control.

2. Activity 8.3.1.4.1.2 (integration of geophysical activities): This activity was to provide a mechanism for information exchange, data analysis, and overview of planned geophysical site characterization activities.

Changes and Status. At the DOE-NRC Technical Exchange in April 1995, a list of 35 boreholes was presented to the NRC as exemplification of the Program Plan of December 1994. The list was generally consistent with plans outlined in the SCP and early study plans, as described above. Of the holes on this list, three boreholes have been drilled since 1995, and three other listed holes plus one new borehole are included in the current long-range plan. Thus, few if any of the remaining 29 listed boreholes identified are likely to be drilled.

1. For the integrated drilling program (8.3.1.4.1.1), although the plans for additional boreholes have been reduced compared with the plans described in the SCP, 11 additional north ramp geologic boreholes were drilled. These boreholes, drilled in support of ESF design, supplemented SCP drilling and provided core from the potential repository horizon that originally was intended to be provided by the proposed (and subsequently canceled) systematic drilling and unsaturated zone boreholes. The lack of additional boreholes was determined as unlikely to increase the risk that available data would be insufficient for the viability assessment and license application. However, absence of the information that might have been provided by the additional boreholes may increase programmatic risk with regard to the consistency of the site characterization reporting as compared with SCP plans, and may reduce confidence in the process models provided to performance assessment. Conservative concepts or parameter values may be used to compensate for the absence of information in process modeling.
2. In the activity to integrate geophysical activities (8.3.1.4.1.2), a comprehensive geophysical testing program (regional- and repository-scale, surface and subsurface, ground-based and aerial surveys) was conducted. Since 1991, 40 boreholes were cored at Yucca Mountain, and 24 new and existing boreholes were logged (under subcontracts to private sector geophysical corporations) with industry-standard wireline geophysical tools. To date 20 of the post-1991 boreholes have been logged and 4 pre-1991 boreholes re-logged with modern wireline geophysical tools.

Nearly 23 miles of deep regional seismic reflection profiling, 35 miles of high-resolution shallow seismic reflection profiling in the repository area, and coincident magnetic and gravity profile data have been collected. The aeromagnetic and ground gravity regional potential field data sets have been synthesized, and final interpretations and subsurface structural models are being generated for further analysis and to support the tectonics, volcanism, and hydrologic investigations. Follow-up documentation for many of the geophysical activities and proposed testing

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programs were presented in the 1990 and 1995 Geophysics White Papers (DOE, 1990; Oliver et al., 1995). Most of the standard and prototype testing programs outlined in DOE (1990) were conducted during the past five years. Enhancements to the 1990 proposals included completion of vertical seismic profiling investigations to repository depths in three boreholes near the potential repository. These investigations are summarized in Majer et al. (1996) and Brocher et al. (in press).

A.1.3.2 Geologic Framework of the Yucca Mountain Site (SCP Investigation 8.3.1.4.2)

Background and SCP Plans. The three objectives of this investigation generally covered those studies and activities that would further allow an understanding of the large-scale variations in stratigraphy and structure needed to support design and performance assessment calculations. First, this investigation was to provide primary data on the lateral and vertical variations in site stratigraphy through the acquisition of borehole cores and cuttings and from surface geologic mapping. Second, the investigation was to provide information that would allow three-dimensional modeling (through the use of borehole and surface geophysical surveys) of the variations in properties of interest between points of primary data. Third, information was to be provided on the lateral and vertical variations of structural elements that may affect in situ properties of interest (e.g., fracture-related flow) in conjunction with site characterization investigations on geohydrology, geochemistry, postclosure tectonics, and seismicity (i.e., preclosure tectonics). This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.4.2.1 (characterization of the vertical and lateral distribution of stratigraphic units within the site area): This study was to (a) determine the vertical and lateral variability, emplacement history, and characteristics of stratigraphic units and lithostratigraphic subunits within the Paintbrush Group, tuffaceous beds of Calico Hills Formation, Crater Flat Group, and possibly older volcanic rocks; (b) improve confidence in stratigraphic models by drilling three additional deep geologic boreholes and by incorporating results from surface-based and borehole geophysical surveys and petrophysical properties testing; (c) determine the distribution of rock properties within lithostratigraphic units; (d) provide magnetic-property data to help interpret volcanic stratigraphy and structure and to assess the rotation of rock units in relation to the geologic structures; and (e) integrate geophysical activities.
2. Study 8.3.1.4.2.2 (characterization of the structural features within the site area): This study was to (a) determine the frequency, distribution, characteristics, and relative chronology of structural features within the Yucca Mountain site area; (b) extend the 1:12,000 scale mapping of zonal features and variations in exposed tuffs of the Paintbrush Group in the site area to help identify structural displacements of 10 m or less and to detect subtle changes in structural styles; (c) conduct surface-fracture network studies to provide measurements and analyses for hydrologic-flowpath modeling of the unsaturated zone and to help develop tectonic models and determine mechanical responses of fractured rock to excavation and thermal loading; (d) conduct

borehole evaluations of faults and fractures to assess reliability and usefulness of borehole techniques, determine vertical and lateral variability and characteristics of subsurface fractures, and identify subsurface characteristics of fault zones; (e) conduct geologic mapping of the ESF to determine vertical and horizontal variability of fracture networks and lithostratigraphic features, characterize major faults and fault zones, and assist in evaluation of test locations; and (f) conduct seismic tomography and vertical seismic profiling to detect and characterize subsurface fracture networks by extrapolating the relation between seismic-propagation characteristics and observed fracture patterns to unexplored volumes of rock.

3. Study 8.3.1.4.2.3 (three-dimensional geologic model): This study was to develop a three-dimensional geologic model of the site area that incorporates stratigraphic, structural, geophysical, and rock properties information pertinent to site characterization, design, and performance assessment activities.

Changes and Status. The objectives of the investigation remain the same as defined in the SCP. The scope of the investigation has, for the most part, followed that described in the SCP, and in some instances has exceeded that scope. The notable exception is the decision not to drill the additional geologic (G) holes. Changes that have occurred in the characterization program are summarized below:

1. In the distribution of stratigraphic units study (8.3.1.4.2.1), the drilling of three deep geologic holes proposed in the SCP has not occurred. These holes were intended to investigate lithostratigraphic and structural conditions associated with the large hydraulic gradient in the saturated zone just north of the site area in Yucca Wash, to provide data on the thickness of key lithostratigraphic units in the vicinity of Windy Wash, and to provide data on the thickness of the Paintbrush Group southwest of Busted Butte. The three geologic holes were to be targeted at the corners of the site area and serve as control points for geologic modeling and interpretations of seismic-reflection profiles. Although the Project has completed an important set of boreholes not anticipated by the SCP (eleven north ramp geologic boreholes), and successfully implemented an extensive surface and borehole geophysical studies program, a primary purpose of the three geologic boreholes as not been met. This purpose involves determining (a) the depth to the top of the Paleozoic rocks and the configuration of the Tertiary-Paleozoic contact underlying Yucca Mountain, and (b) stratigraphic and structural controls on the large hydraulic gradient north of the site. These features have potentially important implications for flow of water under the repository area in the saturated zone and the possible migration of radionuclides away from the potential repository. Once the uncertainty in the most representative explanation for each of these features has been determined, the potential implications of these features for long-term isolation of radionuclides at the Yucca Mountain site can be evaluated. When these uncertainty analyses have been completed, the importance of additional characterization of these features to reduce uncertainty in performance predictions can be ascertained.

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The SCP scope has been exceeded in the measurement and verification of stratigraphic sections, revision of the stratigraphic nomenclature, and development of a detailed microstratigraphy for characterization of features observed in core holes. In addition, although not all the areas and features targeted in the SCP were covered, an extensive surface-based geophysical-survey program has been completed, including nearly 23 miles of deep regional seismic-reflection profiling, 35 miles of shallow high-resolution seismic-reflection profiling in the site area, and coincident magnetic and gravity surveys of the site area. The integration of geophysical activities was deleted from this study in Revision 7 of the Site Characterization Program Baseline because the integration is being performed under Investigation 8.3.1.4.1.

2. In the structural features study (8.3.1.4.2.2), recognized inadequacies in available surface maps and changes in criteria for stratigraphic units have resulted in an intensive program to remap and to evaluate existing maps of the site area. Geologic mapping at a scale of 1:6,000 has been performed in an area extending from Comb Peak in the north to Abandoned Wash in the south, and from Jet Ridge in the west to Midway Valley in the east. Although detailed geologic mapping of zonal features was not extended as far south as originally planned (see SCP p. 8.3.1.4-67), detailed mapping was extended northeast of Yucca Wash to include several faults that affect the repository-area structure, and to elucidate important stratigraphic-facies issues. Several pavement studies and detailed surface-mapping exercises have generated a wealth of fracture data for the development of site-area fracture models. With reconfiguration of the ESF from vertical shafts to ramps and alcoves, the strategy and methods for mapping fracture networks, faults, and lithostratigraphic features have changed considerably. The most notable of these changes has been the acquisition of a large volume of data collected through detailed line surveys and full periphery mapping of the ESF.

Although vertical seismic profiling has been completed to repository depths in 10 available boreholes near the potential repository, the scope and strategy for vertical seismic profiling have changed significantly. Initial plans were to test this method in borehole USW G-4 (for vertical seismic profiling) and in the C-holes for the cross-hole tomographic imaging. USW G-4 was selected because of its proximity to the planned vertical shaft of the ESF. When the ESF configuration was modified to ramps and drifts, testing in USW G-4 became less important. Consequently, multi-offset vertical seismic profiling using P- and S-waves were first used in USW NRG-6, a borehole close to the ESF north ramp, and in USW WT-2, a borehole close to the Ghost Dance fault. Both surveys met the objectives of the study plan, in that fracture/fault characteristics were inferred from the data. Subsequent vertical seismic profiling surveys in additional holes (USW G-2, USW G-4, USW SD-12, UE-25 RF#7a and UE-25 RF#4) were performed using P- and S-wave sources for defining shallow S-wave structure for input to site seismic-response models.

In addition, vertical seismic profiling data were collected in a state-of-the-art testing program at borehole UE-25 UZ#16; data from this investigation are being interpreted.

Tomographic studies will not be done at USW UZ-16 because drilling the boreholes, which would have supported gaseous-phase investigations, has been deleted from the program.

Cross-hole tomographic imaging in the C-holes was completed as planned. No additional tomographic work is planned because of the lack of available closely spaced boreholes that penetrate sufficient intervals in the saturated zone. (The length of the holes beneath the water table must be at least twice the hole separation.) Available seismic sources will not operate in dry holes and give the required data quality. The tomographic imaging of the ESF has not yet been performed because ESF construction is not complete.

3. In the three-dimensional geologic-model study (8.3.1.4.2.3), the SCP strategy has evolved considerably. Whereas the original three-dimensional geologic model was envisioned to be primarily "conceptual" and to encompass a series of isopach and structural contour maps, correlation diagrams, and cross sections, the present model is a three-dimensional, computer-based stratigraphic, structural, and properties model (see Section 3.3.5 of this progress report). Presently, the integrated site model includes a geometric representation of selected rock units and structures (the geologic framework model) and a set of rock-properties models and data sets. The geologic framework model encompasses a 166 km² rectangular area around the Controlled Area Boundary and includes more than 30 lithostratigraphic layers between the land surface and the top of the Paleozoic rocks. The 21 faults included in the model are those that are longer than 2 miles (3.2 km) with offsets greater than 100 ft (30.5 m), or are of significance to other studies, or both. Rock properties in the integrated site model include matrix porosity, bulk lithophysal porosity, saturated hydraulic conductivity, density, thermal conductivity, mineralogy, and apparent ages and isotopic ratios for the Topopah Spring Tuff welded interval at the repository horizon.

A.1.3.3 Development of Three-Dimensional Models of Rock Characteristics at the Repository Site (SCP Investigation 8.3.1.4.3)

Background and SCP Plans. The purpose of this investigation was to synthesize and integrate information collected from various laboratory and field investigations into comprehensive three-dimensional, computer-based models of rock characteristics. The studies were intended to document vertical and lateral variations in rock properties, to provide information and statistical testing necessary to permit modeling of properties between control points, and to characterize key rock property variations in the site area. The investigation provides a variety of work products, such as geologic maps and cross sections, to design and performance assessment groups. These work products typically depict variations in physical properties such as rock compressive strength, thermal conductivity, gas permeability, or fracture density.

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The SCP and derivative study plans specified that the majority of data for this investigation would be obtained from 7 to 12 systematic drilling boreholes to be drilled in the repository area, and from unsaturated zone boreholes located along the perimeter of the potential repository area. Additional data for the rock properties modeling investigation were to be provided by various unsaturated zone boreholes.

The objectives of this investigation were to characterize the three-dimensional distribution of rock characteristics, and hydrologic and geochemical variables, for the unsaturated zone at Yucca Mountain; integrate quantitative and semiquantitative data on rock characteristics; and apply the results.

1. Study 8.3.1.4.3.1 (systematic acquisition of site-specific subsurface information): This study was to acquire rock samples, analytical data, and basic descriptions of the subsurface geology of the repository site on a systematic basis.
2. Study 8.3.1.4.3.2 (three-dimensional rock characteristics models): This study was to develop computer-based three-dimensional models that integrate quantitative and semiquantitative data on rock characteristics in light of constraining information developed by studies of the geologic framework of the Yucca Mountain site (Investigation 8.3.1.4.2).

Changes and Status. The primary objectives of the investigation remain the same, with minor modifications, and include acquiring rock samples and determining physical properties, presenting the analytical data, providing a basic description of subsurface rock characteristics derived from systematic drilling and unsaturated zone boreholes, and presenting rock properties variations as three-dimensional computer-based numerical models. The investigation objectives require a broad scope of activities. One major enhancement to the SCP program was the amplification of the responsibilities for integration of results from Investigation 8.3.1.15.1 (thermal and mechanical rock properties), which was an aspect of the investigation never clearly identified in the SCP. Also, minor task adjustments moved the majority of stratigraphy and structural synthesis and associated model development to Investigation 8.3.1.4.2 (geologic framework of Yucca Mountain).

1. In the study to systematically acquire site-specific subsurface information (8.3.1.4.3.1), the Catalog of Planned Boreholes (CRWMS M&O, 1993a) and FY 1994 and 1995 Program Plans presented proposals to drill 12 systematic drilling boreholes and reduced the number of planned unsaturated zone holes to 14. A subsequent major scope change for this investigation is that now 3 of the 12 systematic drilling boreholes are planned to support the license application. However, the number of systematic drilling boreholes eventually drilled may exceed 3 depending on the results of characterization and modeling of rock properties and as-built design information obtained from ESF construction.

Outside the scope of the SCP investigation, Nye County officials are also recording fluid pressure data at boreholes UE-25 NRG#4 and UE-25 ONC#1) supporting long-

term and short-term monitoring of drilling and excavation effects on the ambient pressure and thermal system within Yucca Mountain (i.e., they are documenting changes in ambient conditions induced by the effects of perturbation of the ambient system by the tunnel boring machine). Larger-scale bulk properties, notably bulk density, are being estimated using sensor responses in these boreholes, and these estimates will provide a level of support to the thermal design process that was not anticipated in the SCP.

2. In the study to develop three-dimensional rock characteristics models (8.3.1.4.3.2), plans are to complete assessment of rock properties data derived from borehole and ESF samples, to prepare models of the various rock properties, and to provide rock properties models to various performance assessment activities. Information needs identified during the development of these models will be used to evaluate the need to drill additional systematic drilling boreholes.

A.1.4 Climate Program (SCP Section 8.3.1.5)

Evaluation of the available data on recent climate, meteorology, and paleoclimate indicated that more data were required than were available on the paleohydrology, paleoclimate, and modern climate of the Yucca Mountain area in order to adequately predict future climate and its possible effects on site hydrology relative to repository performance. The SCP climate program was developed to provide data on past, present, and future climate conditions and to determine the effects of climate change on surface, unsaturated zone, and saturated zone hydrology. Specifically, the effects of future climate on geohydrology were to be determined to provide input to performance assessment and design.

The investigations included in the climate program are summarized in the following sections.

A.1.4.1 Studies to provide the information required on nature and rates of change in climatic conditions to predict future climates (SCP Investigation 8.3.1.5.1)

Background and SCP Plans. The objective of this investigation was to provide recent meteorological data and Great Basin historical climate data for use in calibrating (using present conditions) and validating (using past conditions) models of future climate. A paleoclimate-paleoenvironment synthesis was to be developed from data from studies of lake, playa, and marsh sediments, packrat middens, vegetation calibrations, and soil and surficial deposits. This synthesis was to provide time-sequential reconstructions for the modeling activities as well as for Investigation 8.3.1.5.2. These models were to attempt to forecast climatic variables for the next 100,000 years to determine climatic conditions. This investigation included six studies developed to accomplish the following:

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1. Study 8.3.1.5.1.1 (characterization of modern regional climate): This study was to (a) characterize modern regional climate to provide a baseline for the interpretation of climatic variation; (b) characterize synoptic climate to determine modern spatial and temporal variations in precipitation, air temperature, cloud cover, and other meteorological variables; (c) develop modern vegetation-climate calibration relationships, assess lake-climate relationships, and develop and test climate-circulation models to specify relationships between global-scale circulation patterns and the regional and local climate features of relevance to site performance; and (d) determine the climate conditions (i.e., time, temperature, seasonality, and air masses) under which recharge occurs.
2. Study 8.3.1.5.1.2 (paleoclimate study: lake, playa, and marsh deposits): This study was to (a) establish the nature, timing, duration, and amplitude of paleoclimate changes based on analyses of paleontologic, geochemical, and stratigraphic-sedimentologic data obtained from lacustrine sediments in or near southern Nevada; (b) assemble and interpret, in paleoclimatic terms, detailed records of ostracodes, diatoms, and pollen, and other types of fossils to identify, enumerate, and interpret paleontologic data that emphasizes the past 50,000 years in great detail, the past 200,000 years in moderate detail, and the past 1,000,000 years in some detail; (c) identify and characterize the general physical and chemical properties of sedimentary units from outcrops, shore deposits, and cores to determine their physical and relative temporal framework; (d) analyze the chemical and mineralogic characteristics of sediments to determine the chemistry of the water from which the minerals precipitated and to determine sediment provenance; (e) determine the specific environment of deposition for the sedimentary units; and (f) obtain an accurate, precise chronologic framework of the lake, playa, and marsh deposits sampled in this study.
3. Study 8.3.1.5.1.3 (climatic implications of terrestrial paleoecology): This study was to (a) provide quantitative estimates of changes in climatic variables (e.g., precipitation and temperature) for the southern Great Basin; (b) determine the nature, timing, duration, and magnitude of past vegetation change as recorded in plant macrofossil assemblages preserved in ancient packrat middens for the last 50,000 years and in the stratigraphic record of fossil pollen grains for the last 150,000 years; and (c) translate the vegetational records provided by packrat midden and palynological investigations and available dendroclimatological data into quantitative estimates of past climatic variables.
4. Study 8.3.1.5.1.4 (paleoenvironmental history of the Yucca Mountain region): This study was to (a) evaluate the paleoenvironmental record at Yucca Mountain and surroundings in light of the inferred paleoclimate history of the southern Great Basin to distinguish between effects of climate related surficial processes from those produced by tectonic activity; (b) conduct soil-properties modeling studies to determine the relations among late Holocene soils and modern climatic parameters, analyze properties of soils at Pahute Mesa and near Tonopah as analogs to soil formation at Yucca Mountain during pluvial conditions, compare properties of early Holocene and

Pleistocene soils to paleoclimatic models that were reconstructed from other lines of evidence, frame climatic scenarios as a function of the depth, distribution, and quantity of pedogenic carbonate and other soil parameters, and to quantify rates of soil development in specific climates for use as a dating tool for Quaternary deposits and ages of fault movements; (c) conduct detailed mapping of surficial deposits in the vicinity of Yucca Mountain to support climate, geomorphic, tectonic, infiltration, engineering, and facilities studies; (d) determine the distribution of major concentrations of calcite-silica vein deposits at or near the ground surface at Yucca Mountain; and (e) document eolian erosion and deposition in the Yucca Mountain area during the last 750,000 years and the associated paleoenvironmental conditions.

5. Study 8.3.1.5.1.5 (paleoclimate-paleoenvironmental synthesis): This study was to conduct a paleoclimate-paleoenvironmental synthesis by comparing paleoclimatic estimates from various proxy data sets and providing summaries of paleoclimatic data in formats required for future climate and paleohydrology investigations.
6. Study 8.3.1.5.1.6 (characterization of future regional climate and environments): This study was to (a) estimate values for regional climatic parameters for the Yucca Mountain area over the next 100,000 years, with special emphasis on the next 10,000 years and provide estimates of future precipitation, temperature, and evapotranspiration for input to hydrologic models; (b) identify and estimate factors controlling global climate over the next 100,000 years, including the extent and climatic effects of ice sheets; (c) provide boundary conditions for regional climate models through the use of general-circulation models; (d) establish the feasibility of using a regional scale numerical climate model for predicting future climatic conditions at Yucca Mountain and then calibrate the model against modern climatic data and validate it with paleoclimatic data; (e) conduct linked global-regional climate modeling to formulate scenarios of future climate in the Yucca Mountain area over the next 100,000 years and to determine the associated meteorological parameters for input to hydrologic and erosion models; and (f) conduct empirical climate modeling to formulate scenarios of future climate in the Yucca Mountain area over the next 100,000 years and to determine the associated meteorological parameters for input to hydrologic and erosion models.

Changes and Status. The objectives of the paleoclimatic effort have not changed since the SCP was issued. These studies remain the foundation of the climate program and the studies to estimate bounds on future climatic conditions. Data from different sample suites was to be used to develop numerical transfer functions for using these data sets to quantitatively estimate past climatic parameters such as precipitation and temperature. Collection of data from different sample media is intended to provide independent lines of evidence, and data from one sample suite could be used to corroborate data from another sample suite. The data sources were intended to be sufficiently extensive that data synthesis could provide a robust basis for describing past and current climatic conditions for modeling purposes. Ultimately, the future climate studies may use the linked model output as numerical input for hydrologic process

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models. Testing activities described in the SCP for this investigation are near completion. Changes that have occurred in the characterization program are summarized below:

1. In the study of modern regional climate (8.3.1.5.1.1), the scope has been limited to determining stable and radiogenic isotopes in samples of modern precipitation to establish baseline data against which to compare the isotopic content of lake, playa, marsh, and paleospring deposits. Meteorological and other climatic data necessary for characterization of modern regional climate have been collected and analyzed in Study 8.3.1.2.1.1 in the geohydrology program and in Investigation 8.3.1.12.1 in the meteorology program.
2. In the study of the paleoclimate of lake, playa, and marsh deposits (8.3.1.5.1.2), efforts have focused on obtaining relevant data sets in all study areas (recent meteorological, aquatic, terrestrial, and surficial) and correlating these data with orbital parameters to produce a time-sequential reconstruction. A significant difference between the current study and that outlined in the SCP is the period of time selected for the most detailed paleoclimate characterization. The current study is focusing most intensively on the last 400,000 years because this time frame represents a full climate cycle consisting of four 100,000-year subcycles, each containing a glacial-interglacial couplet.
3. In the study of climatic implications of terrestrial paleoecology (8.3.1.5.1.3), terrestrial studies have focused on packrat middens to reconstruct the history of vegetation changes and associated climatic variables. This study has proceeded largely as described in the SCP.
4. In the study of the paleoenvironmental history of the Yucca Mountain region (8.3.1.5.1.4), surficial and soil studies have established depositional and erosional regimes in response to climatic changes. Detailed mapping of surficial deposits was completed as described in the SCP, but primarily to support geomorphic, tectonic, infiltration, and engineering studies rather than climate studies. Soil-properties modeling to determine the relationships between soil formation and climatic parameters has been dropped from the study because characteristics of soil formation are unlikely to provide the millennial-scale climate-change information available from other lines of evidence, such as isotopic compositions of deep calcites. Also, soil-properties modeling will not yield information on changes in mean annual precipitation and temperature, which is critical to developing future climate scenarios based on the past.

The origins of major calcite-silica vein deposits were determined in Study 8.3.1.5.2.1 (characterization of the quaternary regional hydrology).

5. In the paleoclimate-paleoenvironmental synthesis study (8.3.1.5.1.5), current efforts are focused on synthesizing and corroborating the various data sets to reconstruct paleoclimatic conditions. These time-sequenced reconstructions were to be used to

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estimate the initial bounds for future climatic conditions and to calibrate the future climate-modeling efforts. This study has proceeded largely as described in the SCP.

6. In the characterization of future regional climate and environments study (8.3.1.5.1.6), limitations in numerical-modeling techniques have resulted in the realization that a full 100,000-year simulation of future climate using the regional climate model is not feasible. Instead, the regional climate model is being used to simulate various possible future climate scenarios (such as the "greenhouse" state) and to produce tallies of precipitation and temperature for two- to five-year periods.

A.1.4.2 Studies to provide the information required on potential effects of future climatic conditions on hydrologic characteristics (SCP Investigation 8.3.1.5.2)

Background and SCP Plans. The objective of this investigation was to develop an understanding of the Quaternary regional hydrologic regime by using the reconstructions of past climate from Investigation 8.3.1.5.1, along with past surface-water, unsaturated zone, and saturated-zone characterizations. The investigation was to determine the hydrologic conditions during the Quaternary that differ significantly from present conditions because of changes in climate. Data from this investigation were intended to assess the nature and likelihood of episodic climatic changes that could produce changes in the regional flow system during the next 100,000 years. This information, along with models of future climate conditions and estimates of future meteorological conditions from Investigation 8.3.1.5.1, and models of the unsaturated and saturated zones from the geohydrology program (SCP Section 8.3.1.2), was to be used to determine the effects of climate change on geohydrology. This determination would require the development of a relationship between climate and infiltration and recharge. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.5.2.1 (characterization of the Quaternary regional hydrology): This study was to (a) characterize the distribution of surface water, unsaturated zone infiltration and percolation rates, and ground-water potentiometric levels during the Quaternary Period in the vicinity of Yucca Mountain; (b) investigate the hydraulic characteristics of paleofloods and compare them with modern flooding and geomorphic processes to improve knowledge of the relationships between climate and flooding; (c) assess the character and severity of potential flood and debris hazards for the repository during the preclosure period; (d) determine the past infiltration and percolation history at Yucca Mountain by analyzing the isotopic and chemical characteristics of water from the unsaturated zone; (e) characterize the hydrogeologic units in the regional ground-water discharge areas of the Amargosa Desert and Death Valley; (f) understand the past quantity and quality of water in the discharge areas of Franklin Lake, Amargosa Desert-River, and Peter's Playa; (g) determine the location and hydrogeologic characteristics of paleospring deposits and the amount of discharge by evapotranspiration that has occurred at past discharge sites; (h) determine past ground-water levels in carbonate caverns as evidence of past hydrologic conditions; (i) use information about past and present discharge areas to help predict the future saturated-

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zone hydrologic system at Yucca Mountain; (j) conduct analog recharge studies to estimate the conditions and rates of ground-water recharge (infiltration) during the Quaternary near Yucca Mountain; and (k) determine the ages, distribution, origin, and paleohydrologic significance of calcite and opaline silica vein deposits along faults and fractures in the vicinity of Yucca Mountain.

2. Study 8.3.1.5.2.2 (characterization of future regional hydrology due to climate changes): This study was to (a) characterize the impacts of potential future climate changes on the regional and site surface-water system, the site unsaturated zone hydrology, and the regional and site saturated zone hydrology; (b) simulate past changes in runoff and surface-water storage (lakes) resulting from past climatic change using precipitation-runoff models calibrated to modern surface-water conditions; (c) use the relationship between paleoclimate and paleo surface-water conditions to predict the impact of future climatic conditions on surface-water hydrology at the site; (d) predict quantitatively the potential effects of future climatic conditions on infiltration, percolation, and the degree of saturation of the unsaturated zone at Yucca Mountain; (e) reconstruct paleohydrologic conditions at Yucca Mountain and use these conditions together with the reconstructed paleoclimatic conditions to predict the impact of future climatic conditions on the saturated zone; and (f) use numerical-simulation techniques to synthesize existing paleohydrologic data and to determine the effects of greater recharge on water-table altitude, ground-water flow paths, and hydraulic gradients.

Changes and Status. The objectives of this investigation have not changed since the SCP was issued. However, the investigation has been modified to take advantage of data available from other sources. The investigation is intended to determine the effect of past climate change on hydrologic conditions and then use that understanding as the foundation for the evaluation of future effects of climate change on hydrologic conditions. Changes that have occurred in the characterization program are summarized below:

1. The Quaternary regional hydrology study (8.3.1.5.2.1) has changed significantly since the SCP was issued. For example, the Quaternary unsaturated zone hydrochemical analysis planned originally under this study has been transferred to Study 8.3.1.2.2.7 (characterization of the unsaturated zone hydrochemistry). Further, although a study of paleoflooding and the potential for future extreme flooding was conducted in Coyote Wash at Yucca Mountain (Glancy, 1994), additional studies of alluvial deposits in neighboring washes and throughout the region surrounding Yucca Mountain never were conducted. This is because there was less concern about flood and debris hazards potentially impacting the ESF or surface facilities after the ESF was reconfigured from vertical shafts to ramps and drifts. Furthermore, the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k) concluded that flooding of the repository by extreme runoff during the preclosure period was extremely unlikely given the location and elevation of the ESF.

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Much of the work planned for the evaluation of past discharge areas has been completed. This includes remote sensing of pedogenic carbonate deposits, vegetation, and fracture zones; measurement of discharge from springs and seeps; measurement of water levels in wells, caverns, and springs; studies of past water levels in carbonate caverns; chemical and isotopic analysis of hydrogenic deposits; and studies of ostracode ecology. However, some characterization work described in the SCP either has not been conducted or has been accomplished under other studies. For example, a drilling program to sample subsurface materials was not implemented because subsurface sampling also was being conducted under Study 8.3.1.5.1.2 (paleoclimate study: lake, playa, and marsh deposits). Also, the characterization of hydrogeologic units in the regional ground-water discharge area has been accomplished using available data under Study 8.3.1.2.1.3 (characterization of the regional ground-water flow system). In contrast, efforts to characterize surficial pedogenic deposits and the history and origin of paleosprings and lake ecology have expanded significantly in scope and complexity. Studies to determine the origin and age of hydrogenic deposits have intensified and have been enhanced and advanced considerably through the application of state-of-the-science isotopic methods including strontium, uranium-series disequilibrium, and stable carbon and oxygen analyses.

The entire analog-recharge study was terminated because the value of study results to Yucca Mountain was very marginal. Two small watersheds in central Nevada were instrumented and studied for several years as "analog recharge" sites; the effort, however, never was expanded to the four or five sites envisioned in the SCP. Similarly, a study of an "arid-zone, monsoonal" site in Arizona was initiated but then terminated before any significant results could be obtained.

Studies of calcite and opaline-silica vein deposits have been expanded substantially in scope and complexity. Whereas the SCP outlined sampling and analysis of fault and fracture fillings found in trenches, natural exposures, drill cores, and spring and pedogenic deposits, the current study has undertaken an intensive effort to sample and analyze occurrences of secondary calcite and silica in fractures, fault zones, and lithophysal cavities in the ESF. This expansion was in response to a need to reconstruct the history of percolation in the Topopah Spring Tuff at the potential repository horizon. Although the study has focused on the repository horizon, representative samples have been collected from the entire length of the ESF as excavation has proceeded. The study has concentrated on the application of strontium and stable carbon and oxygen isotope ratios to determine the source of water and the mode of mineral deposition, uranium-series and radiocarbon dating methods to determine timing of mineral deposition, and petrographic examination to determine the sequence of mineral deposition. The goal of these studies is to use the history and distribution of secondary-mineral deposition in the deep unsaturated zone to estimate or bound percolation rates through the repository block over the past several hundred thousand years.

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2. In the study of future regional hydrology due to climate changes (8.3.1.5.2.2), efforts to develop precipitation-runoff models of modern surface-water conditions and basin characteristics were terminated because runoff occurs so infrequently that collecting data sets sufficient to calibrate the models was not feasible. Regional ground-water modeling studies (D'Agnese et al., 1996b) did not require runoff data for calibration because a direct relationship between precipitation and ground-water recharge was used. The impact of future climate on the ground-water system was identified as more important for evaluating repository performance than the impact of future climate on the surface-water system. Consequently, plans to use these models to predict future runoff conditions resulting from hypothesized climatic change also were dropped from the characterization program.

As reported in Revision 9 of the Site Characterization Program Baseline, the analysis of impacts of future climate changes on the unsaturated zone have been deleted from this study and will be performed under Activities 8.3.1.2.2.9.3 and 8.3.1.2.2.9.5. Similarly, the effects of possible future recharge from climate changes on the saturated zone are being evaluated under Studies 8.3.1.2.1.4 (regional hydrologic system synthesis and modeling) and 8.3.1.2.3.3 (site saturated zone hydrologic system synthesis and modeling).

A.1.5 Erosion Program (SCP Section 8.3.1.6)

Data available when the SCP was written suggested that the proposed repository could be constructed deeper than the minimum depth of 200 m and that erosion was unlikely to uncover or affect the repository at the planned depth (DOE, 1986). Long-term average upland and hillslope erosion rates had been established for the southern Great Basin and many of the parameters necessary to estimate erosion rates in the region had been obtained from ongoing scientific studies at the Nevada Test Site. Few of these data, however, were specific to the proposed repository site. Therefore, the erosion program was designed to provide representative, site-specific data about present and past locations and rates of erosion, effects of future climatic conditions and future tectonic activity on locations and rates of erosion, and potential effects of erosion on selected other site features and processes.

The investigations included in the erosion program are summarized in the following sections.

A.1.5.1 Studies to Determine the Distribution and Characterization of Present and Past Erosion (SCP Investigation 8.3.1.6.1)

Background and SCP Plans. The objectives of this investigation were to identify the erosional processes that have been operating in the Yucca Mountain area during the Quaternary, to identify the specific locations of past erosion, and to quantify the rates of the different

processes and assess their relative importance. This investigation included one study developed to accomplish the following:

Study 8.3.1.6.1.1 (distribution and characteristics of present and past erosion): This study was to (a) determine the areal distribution of active erosional areas and geomorphically stable areas and determine the spatial distribution of the different types of geomorphic processes and associated deposits; (b) determine stream-incision rates on Fortymile Wash and selected tributaries and determine the cause(s) of the major downcutting episode(s) on Fortymile Wash; and (c) determine the average rates of Quaternary hillslope erosion on Yucca Mountain in bedrock and surficial deposits and determine the genesis and rates of movement of hillslope deposits.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessments, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

All objectives identified in the SCP have been fulfilled to address the DOE siting guidelines (10 CFR Part 960) and the NRC performance requirements (10 CFR Part 60) as specified in these regulations. Some of this information was reported to the NRC in a topical report (DOE, 1993d) containing the DOE evaluation of the extreme erosion potentially adverse condition, in the responses to the NRC staff comments on the Extreme Erosion Topical Report (DOE, 1995s) and supplemental responses contained in a letter dated June 28, 1996 (CRWMS M&O, 1996oo). Other parts of the information have been (a) presented in the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k) (b) forward-referenced to outputs in the Project Integrated Safety Assessment; (c) fulfilled with surrogate information gathered under other SCP Programs; or (d) rendered unnecessary based on early stages of the investigation and evaluation of the need for additional data to support assessments of performance of the potential repository. Quaternary denudation rates on hillslopes and stream incision rates in the major alluvial system at Fortymile Wash confirmed the DOE expectations and indicated that no additional data collection was required. In 1991, DOE decided to document the results obtained in a topical report (DOE, 1993d) as planned in Investigation 8.3.1.6.4, terminate data collection, and not implement Investigations 8.3.1.6.2 and 8.3.1.6.3. The NRC was officially informed that study plans would not to be developed for the erosion program (DOE, 1994i).

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The work for the erosion program began in the 1980s under a U.S. Geological Survey (USGS) Scientific Investigation Plan (Whitney, 1987) and later through SCP study plans that had been prepared for other programs of the SCP (the Preclosure Tectonics Program, Study Plan 8.3.1.17.4.6: Quaternary Faulting in the Site Area; the Preclosure Hydrology Program, Study Plan 8.3.1.16.1.1: Characterization of Flood Potential at the Yucca Mountain Site; and the Climate Program, Study Plan 8.3.1.5.1.4: Analysis of the Paleoenvironmental History of the Yucca Mountain Region). Data gathered under these studies were used to describe erosional processes, measure the extent of erosion, and calculate erosion rates. The erosion rate estimates and information indicating the overall stability of the landscape indicated that additional analysis and data collection were unnecessary. These results were documented in the Extreme Erosion Topical Report (DOE, 1993d). Similar interpretations were described in the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion which stated: "Studies of erosional processes at the Yucca Mountain Site suggest that the landscape at the Yucca Mountain Site has changed very little during the past several hundred thousand years due to erosion." (DOE, 1995k, p. 5-1).

Because of NRC staff concerns with the age estimation method used by DOE to determine ages of colluvial boulder deposits, the DOE authorized a modest program to collect cosmogenic ages for selected deposits (CRWMS M&O, 1996oo) under Study 8.3.1.5.1.4: Analysis of the Paleoenvironmental History of the Yucca Mountain Region. Information from this study was expected to corroborate the ages determined previously and support DOE's conclusions about the erosion rates, and the age and stability of the landscape (DOE, 1995k). Given the proposed depth of the potential repository of at least 200 m (DOE, 1995k), and based on the stability of the landscape and the very low rates of hillslope erosion (DOE, 1993d; DOE, 1995k), it is unlikely that hillslope erosion poses a significant risk to repository performance.

In Study 8.3.1.6.1.1 data were obtained from other studies to determine the age of alluvial deposits and stream incision rates in Fortymile Wash and Midway Valley, and the age of colluvial boulder deposits and erosion rates on hillslopes. Information on the depth of stream incision, stream gradients, and lithologic composition of gravels in the Fortymile Wash drainage system was collected under studies in the climate program and is reported in Lundstrom and Warren (1994). Dating of surficial alluvium, soils, and terraces was reported in Paces et al. (1995) and is discussed in CRWMS M&O (1996oo).

A volumetric analysis of Quaternary alluvium removed in Midway Valley based on the results of surficial deposits mapping in Study 8.3.1.5.1.4 was reported in CRWMS M&O (1996oo).

A.1.5.2 Potential effects of future climatic conditions on locations and rates of erosion (SCP Investigation 8.3.1.6.2)

Background and SCP Plans. The objectives of this investigation were to determine the effects of future climatic conditions on the locations and rates of erosion, especially areas with the potential for increased erosion or stream incision, and apply the results to the evaluation of

site processes that could degrade the surface marker system. This investigation includes one study to accomplish the following:

Study 8.3.1.6.2.1 (potential effects of future climatic conditions on locations and rates of erosion): This study was to determine the effects of future climatic conditions on the locations and rates of erosion by integrating Quaternary climate conditions and rates of surface erosion with predicted conditions of future climate, and by estimating significant changes in the character, distribution, and rates of surface erosion in the Yucca Mountain region over the next 10,000 to 100,000 years.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. However, on the basis of data collected in other site characterization programs and analyses done for Investigation 8.3.1.6.1, DOE determined that erosion rates are extremely low and that the potential impacts on repository system performance are negligible. Thus, the DOE decided not to implement Investigation 8.3.1.6.2, and the NRC was officially informed that study plans would not be developed (DOE, 1994i).

The present locations and rates of surface erosion and their relationships to present climate are discussed in the Extreme Erosion Topical Report (DOE, 1993d), Coe et al. (1995), and Whitney and Harrington (1993). The distribution and characteristics of past erosion and their relationships to past climatic conditions are discussed in Glancy (1994), Whitney and Harrington (1993), and in CRWMS M&O (1996oo). DOE has concluded that climatic influences on erosion are minimal. Climate fluctuations of the type that can be discerned over the last 10,000 to 100,000 years with proxy data from the geologic record bound the expectation for future conditions. DOE's data and analyses support the conclusion presented in the Extreme Erosion Topical Report (DOE, 1993d) that erosion rates have been very low during the last half of the Quaternary Period. In fact the erosion rate is so low that DOE concluded that the potentially adverse condition on extreme erosion (10 CFR 60.122(c)(16)) is not present at the site, and erosion is unlikely to have any significant impact on performance of the potential repository.

A.1.5.3 Studies to provide the information required to determine the potential effects of future tectonic activity on locations and rates of erosion (SCP Investigation 8.3.1.6.3)

Background and SCP Plans. The objectives of this investigation were to identify the potential effects of tectonic activity on erosion at Yucca Mountain during the postclosure period by defining those components of erosion that were dependent upon tectonic activity, determining how future tectonic adjustment might influence local incision rates, and applying the results to the assessment of the potential for degradation of the surface marker system. This investigation included one study developed to accomplish the following:

Study 8.3.1.6.3.1 (evaluation of the effects of future tectonic activity on erosion at Yucca Mountain): This study consists of a single synthesis activity that was intended to estimate (a) the effects of tectonic activity on erosion over the repository postclosure period using

DOE completed the topical report on extreme erosion (DOE, 1993d) and used the report to fulfill the intention described in the SCP. A second topical report will not be developed because of the extremely low erosion rates determined for the arid region and the erosion-resistant rock type at Yucca Mountain. Potential performance impacts from erosion over time were discussed in the supplemental responses to the NRC comments (DOE, 1995s, pp. 2-39 and 2-40) on the Extreme Erosion Topical Report. Rates of erosion at Yucca Mountain have been shown to be so low (DOE, 1993d; DOE, 1995s, pp. 2-39 and 2-40) that it is extremely unlikely that erosion could remove enough overburden to impact repository system performance.

A.1.6 Rock Dissolution Program (SCP Section 8.3.1.7)

The objective of this investigation was satisfied by the information presented in the Yucca Mountain Environmental Assessment (DOE, 1986).

The investigation included in the rock dissolution program is summarized in the following section.

A.1.6.1 Rates of dissolution of crystalline and noncrystalline components in tuff (SCP Investigation 8.3.1.7.1)

The objectives of this investigation were satisfied by the information presented in the Yucca Mountain Environmental Assessment (DOE, 1986). Therefore, no additional testing was proposed in the SCP. The potential for dissolution to occur in conjunction with thermally driven fluid flow and condensation in the repository environment is being addressed in the altered zone study (see Section A.1.15).

A.1.7 Postclosure Tectonics Program (SCP Section 8.3.1.8)

The postclosure tectonics program specified in the SCP was predicated on performance and design requirements (e.g., 10 CFR 60.122 and 10 CFR 960.4-2-7) to investigate, and provide data about, the probabilities and effects of tectonic "initiating events" that might alter existing conditions at Yucca Mountain and adversely affect repository performance. Five investigations were identified and included in the postclosure tectonics program. As the following discussion indicates, the first four investigations were intended to provide data collection, and the last investigation was intended to provide analysis of the data collected by the previous investigations.

Because many elements of these investigations have been consolidated since the SCP was issued, the summaries for Investigations 8.3.1.8.2, 8.3.1.8.3, and 8.3.1.8.4 have been combined into Section A.1.7.2.

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DOE completed the topical report on extreme erosion (DOE, 1993d) and used the report to fulfill the intention described in the SCP. A second topical report will not be developed because of the extremely low erosion rates determined for the arid region and the erosion-resistant rock type at Yucca Mountain. Potential performance impacts from erosion over time were discussed in the supplemental responses to the NRC comments (DOE, 1995s, pp. 2-39 and 2-40) on the Extreme Erosion Topical Report. Rates of erosion at Yucca Mountain have been shown to be so low (DOE, 1993d; DOE, 1995s, pp. 2-39 and 2-40) that it is extremely unlikely that erosion could remove enough overburden to impact repository system performance.

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The investigation included in the rock dissolution program is summarized in the following section.

A.1.6.1 Rates of dissolution of crystalline and noncrystalline components in tuff (SCP Investigation 8.3.1.7.1)

The objectives of this investigation were satisfied by the information presented in the Yucca Mountain Environmental Assessment (DOE, 1986). Therefore, no additional testing was proposed in the SCP. The potential for dissolution to occur in conjunction with thermally driven fluid flow and condensation in the repository environment is being addressed in the altered zone study (see Section A.1.15).

A.1.7 Postclosure Tectonics Program (SCP Section 8.3.1.8)

The postclosure tectonics program specified in the SCP was predicated on performance and design requirements (e.g., 10 CFR 60.122 and 10 CFR 960.4-2-7) to investigate, and provide data about, the probabilities and effects of tectonic "initiating events" that might alter existing conditions at Yucca Mountain and adversely affect repository performance. Five investigations were identified and included in the postclosure tectonics program. As the following discussion indicates, the first four investigations were intended to provide data collection, and the last investigation was intended to provide analysis of the data collected by the previous investigations.

Because many elements of these investigations have been consolidated since the SCP was issued, the summaries for Investigations 8.3.1.8.2, 8.3.1.8.3, and 8.3.1.8.4 have been combined into Section A.1.7.2.

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The investigations included in the postclosure tectonics program are summarized in the following sections.

A.1.7.1 Studies to provide information required on direct releases resulting from volcanic activity (SCP Investigation 8.3.1.8.1)

Background and SCP Plans. The purpose of this investigation was to assess the probability of future volcanic activity with respect to siting a repository for storage of high-level radioactive waste at Yucca Mountain and gather data on the effects of a potential volcanic eruption should such an eruption penetrate the site. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.8.1.1 (probability of a volcanic eruption penetrating the repository): This study was to (a) synthesize the data collected by other activities on the dating, location, and volume of late Cenozoic volcanic events in the region surrounding the site; (b) investigate time-space patterns of past volcanic activity in the Yucca Mountain region and the possible structural controls of volcanic centers and potential future volcanic centers at and adjacent to Yucca Mountain; (c) use statistical methods to evaluate geophysical data to assess the significance of possible local and regional structures on the area ratio of probability calculation; (d) review geophysical and geochemical data collected near the site to assess whether there were any indications of the presence of crustal bodies that could be the source of future volcanic activity; and (e) revise the estimates of the probability of volcanic disruption of a repository site at Yucca Mountain.
2. Study 8.3.1.8.1.2 (effects of a volcanic eruption penetrating the repository): This study was to (a) summarize the effects of a Strombolian eruption on a repository; and (b) obtain geological parameters for the disruption of a repository by magmatic activity accompanied by hydrovolcanic (magma-water) explosions.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. In the probability of a volcanic eruption penetrating the repository study (8.3.1.8.1.1), the main objective (to estimate the probability of disruption of a repository) has remained the same since the SCP was issued. Data on the location and timing of volcanic events was incorporated into the Probabilistic Volcanic Hazard Analysis [(CRWMS M&O, 1996j) see Section 3.6.2 of this progress report]). The study of the presence of magma bodies in the vicinity of the site using geophysical techniques was performed by the geophysics program and not by the volcanism program. Calculations of the probability of a volcanic eruption penetrating the repository were completed using currently available data. A final set of probability calculations using only qualified data obtained in Study 8.3.1.8.5.1 (characterization of volcanic features) was deferred indefinitely. Probability studies were augmented and tested in 1995 through use of the expert elicitation process. The results of the expert elicitation were reported in the Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada (see Section 3.6.1 of this progress report).

2. The effects of a volcanic eruption penetrating the repository study (8.3.1.8.1.2) has changed substantially since the SCP was issued. Studies of the effects of Strombolian and hydrovolcanic eruptions were replaced by three activities (eruptive effects, subsurface effects, and magma system dynamics) when the study plan was drafted in 1993. The eruptive effects activity was only partially completed (not all measurements from analog centers were completed, nor were all data analyzed). However, based on the results of the Probabilistic Volcanic Hazard Analysis, there appear to be no significant impacts from only partially completing the measurements of analog centers. The subsurface effects activity, which focuses on the processes that control shallow-level intrusion geometries and on hydrothermal alteration in silicic tuffs near shallow basaltic intrusions, now includes the study of chemical and physical changes around dikes. A third aspect of the subsurface studies, modeling of hydrothermal processes near intrusions and implications for their effects on a repository, has been indefinitely deferred. A new magma system dynamics study activity was added; its objectives were to constrain the physical processes that control magma generation and ascent and to determine how these processes relate to probabilistic estimates of future volcanic activity. Further work on Study 8.3.1.8.1.2 has been deferred indefinitely because based on the results of the Probabilistic Volcanic Hazard Analysis, additional work is not needed to support the long-range plan.

The relative importance of precisely evaluating the potential effects of a direct volcanic eruption penetrating the repository are directly related to (a) the probability of having such an event during the time period of regulatory concern, (b) the performance measure of concern, and (c) the significance of these effects. Total system performance assessments conducted to date using bounded estimates of the effects of such events indicate that the probability of occurrence is the most significant aspect of the impact of direct intrusive events on postclosure performance. Therefore, greater effort, including expert elicitation, has been devoted to narrowing the probability uncertainty, and the additional work required to refine the estimates of bounds of direct effects has been deferred.

A.1.7.2 Studies to provide information required on rupture of waste packages due to tectonic events (SCP Investigation 8.3.1.8.2); Studies to provide information required on changes in unsaturated and saturated zone hydrology due to tectonic events (SCP Investigation 8.3.1.8.3); Studies to provide information required on changes in rock geochemical properties resulting from tectonic processes (SCP Investigation 8.3.1.8.4)

Background and SCP Plans. The three investigations were intended to determine the hazards posed to the repository by a variety of tectonic initiating events during the postclosure period. Once the hazards were determined, the investigations were designed to examine the potential effects of these hazards on waste package integrity, saturated and unsaturated zone hydrology, and rock mineralogical and geochemical properties during the postclosure performance period. The testing and modeling proposed was intended to provide data to describe and characterize the magnitudes and rates of tectonic processes that have operated in the past. This information was to provide the basic input for geologic, geochemical, tectonic, and hydrologic models of the site. In turn, these models were to provide the mechanisms for analyzing scenarios that portray the potential future effects of tectonic processes and events that could impact repository performance. Initiating events to be modeled included volcanic and igneous intrusion in the control area, faulting, uplift or tilting of rocks, and changes in stress/strain characteristics resulting from related tectonic or igneous events.

In Revision 11 to the Site Characterization Program Baseline, the three investigations were reconfigured into a single study titled "Tectonic Effects: Evaluations of Changes in the Natural and Engineered Barrier Systems Resulting from Tectonic Processes and Events" (Study 8.3.1.8.2.1, see Section 3.6.3 of this progress report). As indicated in Progress Reports #10 and #11 (DOE, 1994e and 1995i), the five studies that made up the three original investigations became the five activities in the reconfigured study, which was designed to accomplish the following:

1. Activity 8.3.1.8.2.1.1 (formerly Study 8.3.1.8.2.1): Collect and synthesize data to assess the probability and effects of tectonic processes and events that could result in waste package rupture and/or adverse impacts on waste-package lifetime and performance.
2. Activity 8.3.1.8.2.1.2 (formerly Study 8.3.1.8.3.1): Analyze and assess the probability and effects of tectonic initiating events that may result in changes in the average percolation flux rate at the top of the Topopah Spring welded hydrogeologic unit.
3. Activity 8.3.1.8.2.1.3 (formerly Study 8.3.1.8.3.2): Analyze and assess the probability that tectonic initiating events could result in significant changes in the elevation of the water table, changes in the hydraulic gradient, the creation of discharge points in the controlled area, or the creation of perched aquifers in the controlled area.
4. Activity 8.3.1.8.2.1.4 (formerly Study 8.3.1.8.3.3): Analyze possible changes in fracture permeability and effective porosity caused by tectonic events and processes.

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5. Activity 8.3.1.8.2.1.5 (formerly Study 8.3.1.8.4.1): Assess possible local changes in the distribution of rock geochemical properties resulting from tectonic processes and events.

Changes and Status. The objectives of the investigations (now the reorganized study) have not changed since the SCP was issued. The multifaceted studies required as input to modeling and assessments needed to determine the impacts of tectonic events on the hydrologic system were an early focus of the site characterization studies. Studies of volcanic and tectonics effects have been coordinated with performance assessment scenario development and consequence analyses over the past several years. Preliminary geologic, geochemical, tectonic and hydrologic models of the site have been developed. Probabilistic estimates of the magmatic disruption probability have been reported in various progress reports since the 1980s, and in 1996 a Probabilistic Volcanic Hazards Analysis for Yucca Mountain, Nevada (CRWMS M&O, 1996j), was completed. This analysis quantified the probability and uncertainty of volcanic disruption of the repository using formal expert elicitation. As discussed in the description of Investigations 8.3.1.17.3 and 8.3.1.17.4 (Sections 3.13.8 and 3.13.9 of this progress report), characterization of seismic hazards is now complete. In 1997 a probabilistic seismic hazards analysis is intended to provide the basis for assessing the magnitudes and rates of tectonic processes. Event trees that form the basis for scenario development for volcanism and tectonics are now complete. To date, preliminary disruptive scenarios for volcanism, reported in Total System Performance Assessment - 1991 (Barnard et al., 1992; Eslinger et al., 1993) and Total System Performance Assessment - 1993 (Andrews et al., 1994; Wilson et al., 1994), indicate that volcanic effects are not significant to system performance. Changes that have occurred in the implementation of the reorganized study are summarized below:

1. In the effect of tectonics on waste-package lifetime and performance activity (8.3.1.8.2.1.1), the potential for basaltic volcanism in the southwest Nevada Volcanic Field and the implications for Yucca Mountain were analyzed (see Progress Report #10). However, the analysis did not address waste-package lifetime or performance, but a conceptual model of the relation between tectonism and volcanism in the Yucca Mountain region was developed (see Progress Report #11). The model refers to factors that affect the probability of magmatic intrusion through the repository block. No additional work is planned.
2. In the effect of tectonics on percolation flux activity (8.3.1.8.2.1.2), a scoping study was initiated of the effect of tectonic activity (principally faulting) on the hydrologic system in preparation for numerical modeling of tectonic effects. Although the numerical modeling of tectonic effects on percolation flux has been deferred, results of the scoping study and the cross-sectional modeling under Activity 8.3.1.8.2.1.3 will be used to help develop tectonic scenarios that may affect the rate of fluid movement in performance assessment calculations.
3. In the effect of tectonics on the saturated zone and perched water activity (8.3.1.8.2.1.3), a scoping study of the effect of tectonic activity (principally faulting) on the hydrologic system was initiated in preparation for numerical modeling of

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tectonic effects. Further, two-dimensional, cross-sectional numerical modeling of coupled fluid and heat flow in the saturated zone was used to analyze three alternative conceptual models for the large hydraulic gradient [see Progress Report #13 (DOE, 1996j)]. In addition, a preliminary scoping study was conducted of the hydrologic setting under Yucca Mountain to assess how occurrences of perched water may be affected by repository thermal loading and tectonic processes [see Progress Report #14 (DOE, 1996b)]. The occurrence of perched water at boreholes USW UZ-1 and USW UZ-14 was analyzed, as well as its possible implications with respect to lateral flow along the top of the basal vitrophyre of the Topopah Spring Tuff beneath the repository area (see Section 3.6.3 of this progress report). Although additional numerical modeling has been deferred, results of the scoping study and the cross-sectional modeling may be used to help develop tectonic scenarios that may affect the rate of fluid movement in performance assessment calculations.

4. In the effect of tectonics on fracture permeability and effective porosity activity (8.3.1.8.2.1.4), possible buried geologic features were analyzed, as well as conditions that may be causing the large hydraulic gradient in the saturated zone just north of Yucca Mountain (see Progress Report #10). Two-dimensional, cross-sectional numerical modeling of coupled fluid and heat flow in the saturated zone was used to analyze these features and conditions (see Progress Report #13). Although additional numerical modeling has been deferred, results of scoping studies and the cross-sectional modeling will be used to help develop tectonic scenarios that may affect the rate of fluid movement in performance assessment calculations.
5. In the effect of tectonics on rock geochemical properties activity (8.3.1.8.2.1.5), no work has been performed, and none is planned. Observations of rock geochemical properties indicate a wide spatial variability. Bounded estimates of changes in rock geochemistry induced by potential tectonic events are considered to be well within the bounds of the natural variability. Observations also indicate that tectonic processes or events would be unlikely to significantly change the retardation characteristics; therefore, this work has been deferred.

A.1.7.3 Studies to provide the information required by the analysis and assessment investigations of the tectonics program (SCP Investigation 8.3.1.8.5)

Background and SCP Plans. The objectives of this investigation were to provide refined data on the age, location, and volume of young volcanic rocks in the vicinity of the site; gather data concerning the presence of thermal anomalies in the area and data on the geochemical and physical effects of intrusions on the surrounding rock; and establish the regional pattern and rate of Neogene folding. This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.8.5.1 (characterization of volcanic features): This study was to
 - (a) investigate, through drilling, the origin of four aeromagnetic anomalies found in

Crater Flat and the Amargosa Valley which may represent shallowly buried basaltic or silicic volcanic centers or intrusive bodies; (b) establish the chronology of basaltic volcanism and the youngest silicic volcanic activity in the Yucca Mountain region; (c) establish the field geologic relations and the eruptive history of basaltic volcanic centers in the Yucca Mountain region; (d) determine the geochemistry of scoria sequences of different ages at the Lathrop Wells center and older centers in the Crater Flat area; and (e) determine the time-space geochemical variations of the volcanic fields of the southern Great Basin.

2. Study 8.3.1.8.5.2 (characterization of igneous intrusive features): This study was to (a) determine the depth of the curie temperature isotherm by analyses of existing magnetic survey data; (b) collect data on the nature and extent of chemical and physical changes that may occur in the surround tuffs as a result of the intrusion of dikes or sills; and (c) evaluate the local ambient heat flow and local heat flow anomalies in relation to Quaternary igneous bodies.
3. Study 8.3.1.8.5.3 (investigation of folds in Miocene and younger rocks of the region): This study was to establish the pattern, rate, amplitude, and wavelength of post-middle-Miocene folding in the region.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection. The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. The main objectives of the characterization of volcanic features study (8.3.1.8.5.1), to provide field geologic, geochronologic, and geochemical data for volcanism probability calculations, have not changed. However, the methods used to collect the information were modified to take advantage of information available from other sources. Drilling of aeromagnetic anomalies to characterize the composition, age, and volume of possible buried volcanic centers in the Yucca Mountain region has been indefinitely deferred. The study of geochemical variations in basaltic volcanic fields to determine whether volcanism is waxing or waning in the Yucca Mountain region was only partially completed (data were gathered but not analyzed). The geochronology studies to determine the age of the youngest silicic volcanism in the Yucca Mountain

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region were not implemented. Instead, the Project will use geochronologic data from non-Project sources of this information.

2. The objectives of the study to characterize igneous intrusive features (8.3.1.8.5.2) have not changed. Sufficient information is available with which to define reasonable bounds on the probability of future magmatic events in the Yucca Mountain region. This information has been used in an expert elicitation to define a probability density function for future events that may intersect the repository region. These bounding analyses will be used in assessments of total system performance to evaluate the potential consequence of these low probability events.
3. The study of folds in Miocene and younger rocks of the region (8.3.1.8.5.3) was deferred.

A.1.8 Human Interference Program (SCP Section 8.3.1.9)

The postclosure human interference program was developed to address (a) the likelihood of inadvertent human intrusion into a mined geologic disposal system (MGDS), (b) interference with long-term MGDS performance because of human activities, and (c) the possible consequences of such interference events.

The investigations included in the human interference program are summarized in the following sections.

A.1.8.1 Studies to provide the information required on natural phenomena and human activities that might degrade surface markers and monuments (SCP Investigation 8.3.1.9.1)

Background and SCP Plans. The objectives of this investigation were to provide information on active or potentially active natural processes at Yucca Mountain capable of adversely affecting the long-term-survivability of the surface marker system, and utilize the data to determine the most suitable locations for the surface markers and monuments. This investigation included one study developed to accomplish the following:

Study 8.3.1.9.1.1 (an evaluation of natural processes that could affect the long-term survivability of the surface marker system at Yucca Mountain): This study was to (a) identify the potential locations of faulting and volcanic eruption or intrusion that could occur and affect the marker system; and (b) determine the effects of future erosion and deposition on the topographic elements of the controlled area boundary at Yucca Mountain.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The SCP, however, described a more extensive program of data collection.

The studies for this investigation have evolved based on the technical information obtained from the laboratory and field studies, model development and data application activities of the site characterization program. Rapidly increasing scientific understanding, along with periodic total system performance assessment, have enabled focusing the ongoing site characterization program on the remaining uncertainties that are significant to the design, operation and safety performance of the proposed repository. Reevaluation and prioritization of Project needs has been a continuous process based on scientific judgment and resource availability, governed by scientific criteria (a) to ensure that data needed for site description, performance assessment, and design purposes were collected and analyzed, and (b) to eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities.

The study to identify natural events that could disrupt or destroy the surface marker system (8.3.1.9.1.1) was completed generally as described in the SCP. Information concerning natural processes that could affect the long-term survivability of the surface marker system at Yucca Mountain has been briefly summarized and included in a report (Fehr et al., 1996). Suitable locations for the surface marker and monument system were determined as described in the SCP.

A.1.8.2 Studies to provide the information required on present and future value of energy, mineral, land, and ground-water resources (SCP Investigation 8.3.1.9.2)

Background and SCP Plan. The objectives of this investigation were to identify and assess the natural resource potential at the proposed repository site at Yucca Mountain; to collect available data to estimate the future supply, demand, and value of the ground-water resource in southern Nevada, proximal to Yucca Mountain; and to apply the results to determine the likelihood for future exploratory drilling within the boundaries of the perimeter drift. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.9.2.1 (natural resource assessment of Yucca Mountain, Nye County, Nevada): This study was to (a) conduct a geochemical sampling program to evaluate the potential for precious, base, and strategic metals; energy resources; and industrial mineral resources in the vicinity of Yucca Mountain; (b) examine and qualitatively evaluate the available geophysical data base to determine whether any geophysical anomalies are present that may require additional exploration and possibly constrain any known geochemical anomalies; (c) characterize the local geothermal regime as it might relate to repository performance during the postclosure period and assess the geothermal regime in terms of its energy resource potential for either hydrothermal or conductive reservoir thermal systems; (d) determine the potential for the presence or absence of suitable source rocks, reservoir rocks, and traps and seals at and near the site; (e) determine the potential for occurrence of conventional hydrocarbon resources at and near the site, and provide data for an overall mineral and energy resource assessment; and (f) complete an overall mineral and energy resource assessment that identifies mineral resources with current markets, calculates gross and net values for

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identified reserves and resources, and evaluates the resource potential of any identified or undiscovered mineral and energy resources.

2. Study 8.3.1.9.2.2 (water resource assessment of Yucca Mountain, Nevada): This study was to assess the current and projected supply and demand situation for ground water in the geohydrologic study area and estimate the value of the ground-water resource.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The scope has been expanded, however, to include studies formerly included in Investigation 8.3.1.9.3. Given the proposed treatment of human-induced potentially disruptive scenarios (commonly referred to as human intrusion) identified by the National Academy of Sciences, the Project plans to use a stylized human intrusion scenario and compare the long-term performance results with the undisturbed scenario analyses. The use of a stylized scenario precludes the need to precisely identify the probability of having each individual human intrusion event correlated with the attractiveness of the site for potential future drilling.

1. Studies to provide the information required on present and future value of energy and mineral resources (Study Plan 8.3.1.9.2.1) have been or are being implemented using standard industry practices. The results of the assessment of geothermal resources were reported in Flynn et al. (1996), and the results of the assessment of industrial rocks and minerals resources were reported in Castor and Lock (1995). A geochemical sampling program is being implemented as part of the metallic resources study and preliminary investigations on hydrocarbon resources were begun in 1995. Work on the assessment of hydrocarbon resources at the site will be resumed in FY 1997, and the final report is expected during the third quarter of FY 1997. Metallic resources will continue to be assessed and the report is due by the end of the second quarter of FY 1997. The natural resources synthesis report is scheduled for completion during the third quarter of FY 1997. Completion of the synthesis report will conclude all the studies planned in the SCP for the natural resources portion of the human interference program. The scope of this study has been expanded to include work formerly included in Study 8.3.1.9.3.1.
2. Studies to provide the information required on present and future value of ground-water resources (Study Plan 8.3.1.9.2.2) have been or are being implemented using standard industry practices. An additional report summarizing the availability, quality, potential uses, and demand for water resources in the area surrounding Yucca Mountain will be completed during the second quarter of FY 1997, although the investigation will be less extensive and use more modern methods than discussed in Study Plan 8.3.1.9.2.2. For example, Nye and Clark counties have developed sophisticated demographic and water-demand forecasts. Therefore, it may be unnecessary for the Project to produce these forecasts. The scope of this study has been expanded to include work formerly included in Study 8.3.1.9.3.2.

A.1.8.3 Studies to provide the information required on potential effects of exploiting natural resources on hydrologic, geochemical, and rock characteristics (SCP Investigation 8.3.1.9.3)

Background and SCP Plans. The objectives of this investigation were (a) to assess the likelihood of inadvertent human interference in the vicinity of Yucca Mountain by evaluating the potential effects of exploration for, or extraction of, natural resources on the hydrologic characteristics of Yucca Mountain, and (b) to use the results of these assessments as input for expert judgment to estimate the bounds on the probability of inadvertent human interference with, and intrusion into, the potential repository. This investigation included two studies developed to accomplish the following:

1. Study 8.3.1.9.3.1 (evaluation of data needed to support an assessment of the likelihood of future inadvertent human intrusion at Yucca Mountain as a result of exploration for and/or extraction of natural resources): This study was to (a) determine the maximum drilling density and frequency (drillholes per square kilometer per 10,000 years) that can be reasonably assumed for a repository at Yucca Mountain, and (b) determine the extent to which future ground-water withdrawals will modify the expected ground-water flow paths.
2. Study 8.3.1.9.3.2 (an evaluation of the potential effects of exploration for, or extraction of, natural resources on the hydrologic characteristics of Yucca Mountain): This study was to (a) determine the potential effects of future ground-water withdrawals on the hydrologic system at Yucca Mountain; (b) demonstrate that those initiating events identified in the SCP for the human interference issue are not considered sufficiently credible or significant to necessitate additional investigation; and (c) document this evaluation in a topical report.

Changes and Status. It was determined that no unique data would be generated by this investigation, and the entire scope was transferred to Investigation 8.3.1.9.2.

1. Evaluation of data needed to support an assessment of the likelihood of future inadvertent human intrusion as a result of exploration for and/or extraction of natural resources (Study 8.3.1.9.3.1) was transferred to Study 8.3.1.9.2.1 (natural resource assessment of Yucca Mountain, Nye County, Nevada).
2. The study to evaluate the potential effects of exploration for, or extraction of, natural resources on the hydrologic characteristics of Yucca Mountain (8.3.1.9.3.2) was transferred to Study 8.3.1.9.2.2 (water resource assessment of Yucca Mountain, Nevada). As in the case of potentially disruptive human-induced scenarios (i.e., human intrusion) which may penetrate the repository horizon, other anthropogenic effects may be conceived that potentially modify the hydrologic characteristics of the site. Present day conditions will be used to describe the biosphere pathways, and DOE intends to use that same logic when evaluating the potential change in hydrology by anthropogenic processes such as pumping or irrigation.

A.1.9 Meteorology Program (SCP Section 8.3.1.12)

The purpose of the SCP meteorological program was to provide data needed to calculate radiological doses resulting from airborne releases from the repository during the preclosure operational period, to design of surface facilities, and to provide hydrometeorological measurements for hydrologic and climatic studies. The meteorology program was designed to determine (a) regional meteorological conditions, (b) describe atmospheric and meteorological phenomena at potential locations of surface facilities, (c) identify population centers relative to wind patterns in the general region of the site, and (d) identify and describe potential extreme weather phenomena and recurrence intervals. The investigations were created to provide an understanding of the meteorology of the area, including both average and extreme climatic phenomena. These data were intended to provide input to the performance and design issues that assess the preclosure radiological safety aspects of the mined geologic disposal system under normal and accident conditions.

Three of the investigations were directed at various aspects of regional-scale meteorology. These investigations shared common data sources and similar analyses needed to achieve their objectives. Thus, investigations were combined into one planning document, the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b), Revision 1, as described in Section 3.8 of this progress report.

The investigations included in the meteorology program are summarized in the following sections.

A.1.9.1 Studies to provide data on regional meteorological conditions (SCP Investigation 8.3.1.12.1)

Background and SCP Plan. The purposes of this investigation were to characterize the regional meteorological conditions within at least 80 km of Yucca Mountain, extending to Las Vegas, and to coordinate meteorological monitoring efforts with other Project meteorological monitoring programs. The objectives of the investigation were to gather, analyze, and report relevant meteorological data; and to develop a plan that coordinates meteorological monitoring efforts proposed during site characterization by various Project participants.

Two studies were developed to accomplish data collection and coordination of meteorological monitoring:

1. Study 8.3.1.12.1.1 (characterization of the regional meteorological conditions): This study was to (a) provide for acquiring and analyzing appropriate meteorological data and results from relevant studies; and (b) describe regional meteorological characteristics in a summary report.
2. Study 8.3.1.12.1.2 (plan for synthesis of Yucca Mountain Project meteorological monitoring): This study was to develop a plan that would coordinate meteorological

monitoring efforts initiated through Characterization Programs 8.3.1.12 (Meteorology), 8.3.1.5 (Climate), 8.3.1.2 (Geohydrology), and 8.3.1.16 (Preclosure hydrology).

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The work in this investigation was combined with work from related regional meteorology characterization investigations 8.3.1.12.3 and 8.3.1.12.4. These other investigations address regional airflow patterns relative to local population centers, and provide meteorological information needed for the engineering design of surface facilities and for support of radiological dose calculations. The consolidated work plan was developed as Scientific Investigation Implementation Package for Regional Meteorology.

A.1.9.2 Studies to provide data on atmospheric and meteorological phenomena at potential locations of surface facilities (SCP Investigation 8.3.1.12.2)

Background and SCP Plans. The purpose of this investigation was to provide site-specific meteorological data to Project investigators working on a variety of site characterization activities. Applications include calculating radiological doses to workers, including workers in restricted areas, and the general public under routine and accident scenarios. The objective of the investigation was to conduct meteorological monitoring at Yucca Mountain to provide data that can be used in resolving design and performance issues associated with preclosure radiological safety. The investigation includes one study that was developed to accomplish the following:

Study 8.3.1.12.2.1 (meteorological data collection at the Yucca Mountain site): This study was to (a) collect meteorological data at potential locations of surface facilities and at a sufficient number of additional locations deemed necessary to characterize the wind flow patterns in the vicinity of Yucca Mountain; and (b) process the meteorological data collected into a format and content that will be useful in assessing radiological impacts, as required by the design and performance issues.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The work for this investigation is controlled by Study Plan 8.3.1.12.2.1.

In the activity to collect and process meteorological data (8.3.1.12.2.1), the network was expanded from five to nine stations during 1992. Modernization changes have been made to ensure that the data content and quality meet the current regulatory monitoring requirements applicable to input data for atmospheric dispersion models. The modernization changes are consistent with the SCP objectives and ensure that the objectives are being met.

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A.1.9.3 Studies to provide data on the location of population centers relative to wind patterns in the general region of the site (SCP Investigation 8.3.1.12.3)

Background and SCP Plans. The purpose of this investigation was to characterize regional wind flow patterns relative to population centers in the vicinity of Yucca Mountain. This investigation uses data from other regional meteorology and socioeconomic investigations.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The work in this investigation was combined with work from related regional meteorology characterization investigations 8.3.1.12.1 and 8.3.1.12.4. This work is described under Investigation 8.3.1.12.1.

A.1.9.4 Studies to provide data on potential extreme weather phenomena and their recurrence intervals (SCP Investigation 8.3.1.12.4)

Background and SCP Plan. The purpose of this investigation was to provide meteorological data required for engineering design of surface facilities. This investigation included a single study developed to accomplish the following:

Study 8.3.1.12.4.1 (characterize the potential extreme weather phenomena and their recurrence intervals): This study was to (a) evaluate the existing historical, meteorological, and climatological records, technical publications, and other relevant information to quantify the extreme weather phenomena that may be expected at the Yucca Mountain site and (b) to determine recurrence intervals.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The focus on extreme weather events was expanded to include the typical conditions needed by the design engineers. The work in this investigation was combined with work from related regional meteorology characterization investigations 8.3.1.12.1 and 8.3.1.12.3. This work is described under Investigation 8.3.1.12.1.

A.1.10 Offsite Installations and Operations Program (SCP Section 8.3.1.13)

The purpose of the SCP offsite installations program was to provide the data about the operations of facilities which could produce radiological exposures to the public or to site workers as consequences of either normal operations or accidental releases. The investigations including the offsite installations and operations program are summarized in the following sections:

A.1.10.1 Determination of nearby industrial, transportation, and military installations and operations (nuclear and nonnuclear) (SCP Investigation 8.3.1.13.1)

Background and SCP Plans. The objectives of this investigation were to identify and assess the potential impacts on preclosure performance and design from nearby DOE, industrial, transportation, and military operations. This investigation included three data collection activities developed to accomplish the following:

1. Activity 8.3.1.13.1.1 (identify near-site activities): This activity was to (a) identify and describe all DOE, industrial, commercial, transportation, and military operations within 8 km of the Yucca Mountain site; and (b) evaluate significant operations outside this area that could impact the site.
2. Activity 8.3.1.13.1.2 (characterize nuclear fuel cycle facilities in the area): This activity was to identify all nuclear fuel cycle facilities within 80 km of the Yucca Mountain site or within Nevada areas adjacent to Las Vegas.
3. Activity 8.3.1.13.1.3 (characterize all nuclear facilities not associated with the fuel cycle near the Yucca Mountain site): This activity was to characterize the impacts of all radiological operations at facilities within 80 km of the Yucca Mountain site that are not part of the nuclear fuel cycle.

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The activities described in the SCP to meet these objectives have been incorporated in the long-range plan for initiation in FY 1997 and completion in FY 1998. The results will be incorporated in the appropriate sections of the Project Integrated Safety Assessment. None of the activities has changed since the SCP was issued.

A.1.10.2 Potential impacts of nearby installations and operations (SCP Investigation 8.3.1.13.2)

Background and SCP Plans. The objective of this investigation was to use the data collected in Investigation 8.3.1.13.1 to assess the impacts that may result from accidents involving any nearby installations and operations. The potential accidents include radiological and nonradiological events that may impact site operations. This investigation included four activities developed to accomplish the following:

1. Activity 8.3.1.13.2.1 (evaluate near-site activities): This activity was to (a) review all commercial, DOE, Department of Defense, and transportation operations within 8 km of the site; (b) identify those operations that could act as accident initiators; and (c) quantify the probabilities and magnitudes.
2. Activity 8.3.1.13.2.2 (evaluation of the impact of nuclear fuel cycle operations near the Yucca Mountain site and Las Vegas): This activity was to (a) determine the impact of

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all nuclear fuel cycle operations within 80 km of the Yucca Mountain site by determining routine yearly releases of radioactive material from all such facilities based on information in safety documentation; and (b) determine the probabilities and magnitudes of potential accidents at the facilities based on past technical reports and safety analysis documentation.

3. Activity 8.3.1.13.2.3 (evaluate the impact of all nuclear facilities not associated with the nuclear fuel cycle near the Yucca Mountain site): This activity was to use data from Activity 8.3.1.13.1.3 to determine airborne concentrations and estimate the probability of such concentrations resulting from operations within 80 km of Yucca Mountain. These estimates provide the basis to estimate potential for exposure of individuals in Las Vegas, Nevada.
4. Activity 8.3.1.13.2.4 (evaluate the impact of ground motion from nuclear testing activities at the Nevada Test Site): This activity was to evaluate the impact of ground motion from nuclear testing activities at the Nevada Test Site. As described in the SCP (DOE, 1988, p. 8.3.1.13-11) this activity was addressed in the resolution of Investigation 8.3.1.17.3 (studies to provide required information on vibratory ground motion that could affect repository design or performance).

Changes and Status. The primary objectives of this investigation have not changed since the SCP was issued. The activities described in the SCP to meet these objectives have been incorporated in the long-range plan for initiation in FY 1997 and completion in FY 1998.

1. The activity to review all transportation operations near the site and assess their potential as accident initiators (8.3.1.13.2.1) has not changed since the SCP was issued.
2. The activity to evaluate the impact of nuclear fuel cycle operations within 80 km of the site and in Las Vegas (8.3.1.13.2.2) has not changed since the SCP was issued.
3. The activity to characterize impacts of radiological operations within 80 km of the site that are not associated with the nuclear fuel cycle (8.3.1.13.2.3) has not changed since the SCP was issued.
4. As noted above, the activity to evaluate the impact of ground motion from nuclear testing is to be addressed in SCP Investigation 8.3.1.17.3.

A.1.11 Surface Characteristics Program (SCP Section 8.3.1.14)

The SCP surface characteristics program was developed to provide data to ensure that potential repository surface facilities, including openings to the underground, protected public health and safety, were technically feasible, and could be constructed at reasonable costs.

The investigations included in the surface characteristics program are summarized in the following sections.

A.1.11.1 Studies to provide topographic characteristics of potential locations of surface facilities (SCP Investigation 8.3.1.14.1)

Background and SCP Plan. The SCP objective for this investigation was to determine the topographic elevation and relief at the potential surface facility locations to provide a basis for evaluating (a) the surface drainage, flood levels, and erosion characteristics in the vicinity of Yucca Mountain; (b) the cut-and-fill requirements for the design and engineering of the repository surface facilities, and (c) the stability of natural slopes and cut slopes. Topographic maps were to be used in siting surface facilities, roads, and railways.

The SCP (DOE, 1988, p. 8.3.1.14-18) stated that no studies were needed or planned for Investigation 8.3.1.14.1 (topography) because the requirements for this investigation had been satisfied. The SCP also stated (p. 8.3.1.14-25) that no further studies, tests, or analyses were planned.

Changes and Status. The objective remains the same as that stated in the SCP. Testing was not required.

A.1.11.2 Studies to provide soil and rock properties of potential locations of surface facilities (SCP Investigation 8.3.1.14.2)

Background and SCP Plans. The objectives of this investigation were to (a) conduct an exploration program for characterization of the soil and rock conditions that will influence, or be influenced by, the construction of surface facilities; (b) conduct laboratory tests and material property measurements on representative samples of soil and rock; (c) conduct field tests and characterization measurements to determine the in situ physical, mechanical, and dynamic properties of the soil and rock; and (d) apply the results. This investigation included three studies developed to accomplish the following:

1. Study 8.3.1.14.2.1 (exploration program): This study was to (a) review existing site information and conduct a field reconnaissance for the purpose of establishing a preliminary exploration program to include subsurface drilling, test pits, trenching, and geophysical methods; (b) obtain sufficient subsurface data to identify or verify the types, locations, and principal dimensions of all major surface structures making up the proposed project; and (c) fill any gaps in the previous preliminary exploration activity and to make such additional explorations that are necessary to define adequately the subsurface conditions.
2. Study 8.3.1.14.2.2 (laboratory tests and material property measurements): This study was to (a) measure the soil or rock weight and volume components using physical

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property tests; and (b) measure in the laboratory the static and dynamic deformation and strength characteristics of soil and rock samples obtained from the exploratory program.

3. Study 8.3.1.14.2.3 (field tests and characterization measurements): This study was to (a) classify and describe the soil and rock conditions in the field and determine their physical properties; (b) measure the deformation and strength characteristics of in situ soil and rock conditions; and (c) use geophysical methods to measure in situ soil and rock properties, profile the alluvium-bedrock contact, locate discontinuities or other structural abnormalities, and determine the depth, thickness, and lateral extent of soil and rock stratigraphic units.

Changes and Status. The objectives have not changed since the SCP was issued. However, much of the data intended to be collected under this investigation has been collected under investigations in other site programs.

The Site Geotechnical Report, Rev. 0 was completed in FY 1996 and included a comprehensive synthesis of groups of soil and rock characteristics data, including results of geophysical surveys and borehole geophysical logs. A second report, the Surface Facilities Design Report, is planned to include data gathered in the site exploration program and present an analysis of the data. This report is expected to include recommendations for foundation design, minimum footing width, maximum bearing pressure, total settlement estimates, differential settlement estimates, resistance to lateral sliding, passive pressure estimates, and recommendations for site preparation. Neither of these reference documents, which provide compilations of key information supporting the design of the repository and surface facilities, was specifically identified in the SCP.

1. In the exploration program study (8.3.1.14.2.1), a report (USBR, 1992) was published that included the results of pavement mapping and core log data from UE-25 NRG#1. This report focused on the north ramp portal area and surface soil characterization for the north portal pad area. In addition, a cross section was developed for the ESF south ramp using surface mapping data.
2. In the laboratory tests and material property measurements (8.3.1.14.2.2), laboratory testing was completed on samples from the north ramp geologic boreholes and trenches and systematic drilling boreholes for intact rock index properties, mechanical properties, and thermal properties. Laboratory and field tests were completed to characterize the nonlithified Rainier Mesa Tuff and pre-Rainier Mesa Tuff bedded tuff. Laboratory and field tests were completed to characterize soil parameters for foundation design for selected north portal facilities. These data were submitted to the technical data base.
3. In the field tests and characterization measurements study (8.3.1.14.2.3), a report was completed that presents the results of the engineering characterization of the pre-Rainier Mesa Tuff bedded tuff and Rainier Mesa Tuff that were encountered by the

ESF north ramp (Kessel et al., 1994). This report characterized the extent and mechanical properties of the soil-like tuffs found locally west of the Bow Ridge fault. A second report (Brechtel et al., 1995) documents the investigation for the north ramp of the ESF and included core logs for the north ramp geologic boreholes, cross sections with stratigraphic and thermal-mechanical units and rock mechanics lab testing and rock mass quality and rock mass mechanical properties estimates. A third report (Kicker et al., 1995) included core logs for the systematic drilling boreholes and USW UZ-14 borehole and stratigraphic cross section for the main drift, rock mechanics lab test data, and rock mass quality and rock mass mechanical properties estimates.

A.1.12 Thermal and Mechanical Rock Properties Program (SCP Section 8.3.1.15)

The SCP thermal and mechanical rock properties program was developed to provide all site information needed on thermal and mechanical rock properties and on ambient stress and temperature conditions. Data on these properties are needed for a variety of site characterization, process model development, performance assessment, and design activities. The data needed include (a) thermal properties of the host rock for analyses related to waste package design; (b) thermal-mechanical properties of the rock for development of rock properties models and repository design; and (c) in situ stress and temperature conditions for initial and boundary conditions for design calculations, thermal properties of rock for disturbed zone analysis, and bulk properties and radon emanation for radiologic safety analysis.

The investigations included in the thermal and mechanical rock properties program are summarized in the following sections:

A.1.12.1 Studies to provide the required information for spatial distribution of thermal and mechanical properties (SCP Investigation 8.3.1.15.1)

Background and SCP Plans. The objectives of this investigation were to (a) provide laboratory characterization of thermal conductivity and heat capacity and describe the spatial variability of these parameters; (b) provide laboratory characterization of thermal-expansion behavior and describe its spatial variability; (c) provide laboratory characterization of mechanical properties of intact rock and describe their spatial variabilities; (d) provide laboratory characterization of mechanical properties of fractures and describe their spatial variabilities; (e) monitor rock-mass deformation around a vertical shaft and measure horizontal in situ stresses; (f) obtain data on in situ thermal and thermomechanical properties for thermo-mechanical units TSw1 and TSw2; (g) obtain in situ measurements of the mechanical properties of the rock mass for thermomechanical unit TSw2; (h) investigate the effects of the spatial variability of the rock on drift stability, mining excavation activities, and ground supports; (i) evaluate techniques for underground excavation and ground support, for selecting ground supports to be used in different rock types, and monitor drift stability; (j) quantify the emanation of radon into drifts and observe its dispersion with airflow; and (k) measure parameters needed to

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design repository ventilation systems. The investigation of thermal and mechanical properties is divided into eight data collection studies, four studies focused on properties of intact rock using laboratory methods, and four studies focused on properties and performance of the rock mass under repository conditions using in situ testing.

1. Study 8.3.1.15.1.1 (laboratory thermal properties): This study was to obtain laboratory data on (a) density and porosity and evaluate the spatial variability of these parameters; (b) volumetric heat capacity and evaluate the spatial variability of this parameter; and (c) thermal conductivity and evaluate the spatial variability of this parameter.
2. Study 8.3.1.15.1.2 (laboratory thermal expansion testing): This study was to obtain laboratory data for thermal-expansion behavior and evaluate the spatial variability of this parameter.
3. Study 8.3.1.15.1.3 (laboratory determination of mechanical properties of intact rock): This study was to obtain laboratory data for the compressive mechanical properties of intact rock and the spatial variability of this parameter for baseline experiment conditions. Evaluate the effects of varying sample size, strain rate, temperature, confining pressure, lithophysal content, saturation state, and anisotropy on compressive mechanical properties, and measure the tensile strength of thermomechanical unit TSw2.
4. Study 8.3.1.15.1.4 (laboratory determination of the mechanical properties of fractures): This study was to (a) obtain data for the mechanical properties of fractures, and the spatial variability of this parameter for baseline experiment conditions; and (b) evaluate the effects of varying normal stress, displacement rate, temperature, sample size, fracture roughness, and saturation state on the mechanical properties of artificial and natural fractures.
5. Study 8.3.1.15.1.5 (excavation investigations): This study was to (a) monitor rock-mass deformation around a vertical shaft and measure horizontal in situ stresses; (b) demonstrate constructability and stability of underground rooms with cross-sectional dimensions equivalent to those of a repository in both lithophysae-rich and lithophysae-poor material; and (c) obtain data on the deformation response of drifts with cross-sectional dimensions equivalent to those of a repository in welded tuff, evaluate computer code(s), and demonstrate the constructability and stability of repository-sized drifts in lithophysae-rich and lithophysae-poor material.
6. Study 8.3.1.15.1.6 (in situ thermomechanical properties): This study was to (a) estimate the in situ thermomechanical properties of lithophysae-rich tuff (thermomechanical unit TSw1) and to evaluate the thermal and mechanical response of this tuff unit to elevated temperatures; (b) obtain thermal and thermomechanical rock-mass measurements of the effects of thermal inputs on a representative (canister-scale) waste-emplacement borehole in lithophysae-poor tuff (thermomechanical unit TSw2); (c) estimate in situ mechanical and thermomechanical properties of thermomechanical

unit TSw2 and test thermomechanical computer models; (d) monitor changes in thermally induced stress in jointed welded tuffs in an accelerated test; (e) evaluate the thermomechanical response of welded tuff around repository openings to expected repository conditions during both construction and operation; (f) develop a data base for evaluating thermal and thermomechanical design analyses and methods applicable for repository considerations; and (g) use site data in predicting drift response and support-rock interactions during construction, operation, retrieval, and postclosure.

7. Study 8.3.1.15.1.7 (in situ mechanical properties): This study was to (a) measure the deformation modulus of the rock mass and evaluate the zone of increased fracturing adjacent to underground openings; and (b) evaluate the mechanical behavior of the rock mass or its components.
8. Study 8.3.1.15.1.8 (in situ design verification): This study was to (a) develop recommendations for mining [excavating] in the repository by monitoring and evaluating mining [excavation] activities in the ESF, and by conducting mining [excavation] investigations; (b) develop recommendations for a ground-support methodology to be used in drifts in the repository, on the basis of evaluations of the ground-support methodology used in the ESF and on experimentation with other ground-support configurations; (c) provide confidence in predictions of usability of the repository underground facilities over the 100-year operational life; (d) contribute to evaluations of the effectiveness of mining [excavating] methods and ground-supports; (e) calibrate and refine criteria for determining stability of the openings; (f) develop techniques for monitoring stability of the repository drifts; and (g) measure the rate of radon emanation from the repository host rock, and evaluate parameters and variables needed as input to or for testing of the models to be used for design of the ventilation systems in the repository underground facility.

Changes and Status. The basic objectives of this investigation have not changed since the SCP was issued. The laboratory testing program to determine thermal and mechanical properties of intact rock has been scaled down in terms of the numbers of samples to be tested and the spatial extent of testing. This was primarily a result of the reevaluation and prioritization of project needs for performance assessment and design that has evolved over the past two years (DOE, 1994a and 1996a). The spatial variability of rock properties was to be determined from core samples taken from systematic drilling program boreholes. The number of boreholes has been reduced (from 12 to 3) resulting in fewer locations sampled. Samples collected from the ESF will be primarily in the TSw2, resulting in some spatial information in that unit, but the statistical basis for sampling, described in the SCP, will not be followed. Limited information from boreholes is expected to be sufficient for input to the viability assessment, with more information on rock property variability to be developed before submittal of the license application.

The in situ testing related to the determination of rock-mass properties and the behavior of the rock mass under repository conditions has changed because of the development of the Program Approach (DOE, 1994a) and the modifications to the Program Plan (DOE, 1996a). The

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in situ thermal and mechanical studies (primarily study items 5 through 7 above) and the waste package environment studies were reevaluated to produce a new set of proposed tests that accomplished the same set of objectives in a more streamlined fashion. The results of this reevaluation were documented in the In Situ Thermal Testing Program Strategy (DOE 1995j). The In Situ Design Verification Study (study item 8 above) was implemented during the construction of the ESF with only minor modifications.

The changes to the studies included in the thermal and mechanical properties investigation are described briefly below:

1. In the laboratory thermal properties study (8.3.1.15.1.1), extensive characterization of density and porosity was deferred because similar measurements were being made elsewhere in the program. Limited heat capacity measurements in the TSw2 were made using the guarded heat flow meter method. Experimental values compare well with theoretical values already submitted to the Reference Information Base (DOE, 1995m). Because it appears that heat capacity can be adequately predicted by theoretical methods, no additional tests are planned. Experimental data on samples of TSw1, TSw2, PTn, and TCw thermomechanical units from boreholes UE-25 NRG#4, UE-25 NRG#5, USW NRG-6, and USW NRG-7 have been completed. Additional tests of the TSw2 unit from samples collected from the Thermal Testing Facility and the Southern Ghost Dance Fault Alcove are planned to assess spatial variability.
2. In the laboratory thermal expansion testing study (8.3.1.15.1.2), unconfined and confined thermal expansion tests have been conducted on samples from TSw1, TSw2, PTn, and TCw from the north ramp geologic and systematic drilling boreholes. In accordance with the SCP mineralogic characterizations of some specimens were performed so that a correlation between the silica components and thermal expansion behavior could be examined. Also, thermal expansion tests at elevated pressures were performed to examine the effects of confining pressure on nonlinear thermal expansion. Additional testing, not described in the SCP, will be conducted on TSw2 samples from the Thermal Testing Facility and the Southern Ghost Dance Fault Alcove to assess spatial variability.
3. In the laboratory determination of mechanical properties of intact rock study (8.3.1.15.1.3), extensive testing of basic properties has been performed on core from the north ramp geologic and systematic drilling boreholes. Limited creep tests at ambient and elevated temperature have been completed. Effects of environmental conditions such as temperature and pressure have also been investigated, primarily in the TSw2 thermomechanical unit. Because of the need to provide data for ESF design, most of the study activities have focused on the TSw2. Because the remainder of the systematic drilling boreholes will not be drilled, only limited information on spatial variability will be collected from units other than the TSw2.
4. In the laboratory determination of mechanical properties of fractures study (8.3.1.15.1.4), fracture specimens from units TCw, TSw1, TSw2, and CHn were

tested. The constitutive properties resulting from the measurements at selected normal stresses were normal stiffness, shear stiffness, shear strength, and dilation. Fracture tests on TSw2 rock were also conducted at elevated temperature (175°C). This work is within the scope of testing described in the SCP.

5. In the excavation investigations study (8.3.1.15.1.5), the access convergence and demonstration breakout tests have been abandoned because of the change from shaft access to the ESF to ramp access. In addition, some of the information required from these tests will be generated as part of the in situ design verification study (8.2.1.15.1.8). The sequential drift mining test was included in the ESF thermal test as part of the development of the drift for the drift-scale test. Detailed planning for this test was initiated early in FY 1996. The test will be conducted in conjunction with construction of the Thermal Testing Facility. The current plan involves installing multipoint-displacement measuring instrumentation from an access drift to near the location where the heated drift test drift will be excavated. This instrumentation will be in place before the heated drift is excavated, and will measure the near-field rock response as the drift is excavated. The instrumentation installed for this test will remain in place and also be used for the drift-scale thermal test to measure rock response to repository emplacement room heating.
6. In the in situ thermomechanical properties study (8.3.1.15.1.6), the project reevaluated the thermal testing and analysis program and proposed a new, more consolidated suite of tests to accomplish the objectives of thermal testing. This strategy was documented in the In Situ Thermal Testing Program Strategy (DOE, 1995j). The strategy was implemented in FY 1996 by incorporating it into this study and initiating the design and fielding of the first ESF thermal test. This test was composed of two parts—a single heater test and a heated drift test. These tests were identified in DOE (1995j) as principal components of the test strategy. The tests in the study have been modified as follows:
 - Heater experiment in unit TSw1 (Activity 8.3.1.15.6.1). A single heater test in TSw1 was proposed as an alternative test if the ESF construction was delayed (DOE, 1995j). Because of rapid progress in ESF construction, this test is being deferred in favor of testing in the TSw2.
 - Canister-scale heater experiment (Activity 8.3.1.15.6.2). This test was combined with some elements of other tests into the single heater test. A detailed design of the single heater test was completed and documented in Test Design, Plans and Layout Report for the ESF Thermal Test (CRWMS M&O, 1996n). The test was installed in FY 1996 and started in August 1996.
 - Yucca Mountain heated block (Activity 8.3.1.15.6.3). The data needs and objectives related to this test have been combined into the Thermal Testing Facility, under Activity 8.3.1.15.1.6.2 and Activity 8.3.1.15.1.6.5.

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- Thermal stress measurements (Activity 8.3.1.15.6.4). The data needs and objectives related to this test have been combined into the Thermal Testing Facility under Activity 8.3.1.15.1.6.2 and Activity 8.3.1.15.1.6.5.
 - Heated room experiment (Activity 8.3.1.15.6.5). This test has been combined into the heated drift portion of the Thermal Testing Facility. Thermal-mechanical-hydrological-chemical coupling will be explored in this test. A preliminary test configuration has been developed and documented in Test Design, Plans and Layout Report for the ESF Thermal Test (CRWMS M&O, 1996n). The test consists of a single heated drift 5 m in diameter, with in-drift heater canisters to simulate waste packages. To accelerate the test, "wing" heaters will be emplaced in the ribs of the drift. The heated part of the drift will be approximately 50 m long. The heat from the wing heaters will cause the heated part to simulate a drift within a multidrift heated repository. The location and type of instrumentation to be used in the test has been specified in the test plan. The sequential drift mining test, under Study 8.3.1.15.1.5 will be conducted as part of the construction of the heated drift test.
7. In the in situ mechanical properties study (8.3.1.15.1.7), the objectives have been partly incorporated into the ESF thermal tests. A plate loading test will be conducted as part of the heated drift test. This will allow the measurement of rock-mass modulus under both ambient and heated conditions. The planning for this test is taking place as part of the consolidated thermal test and is described in Test Design, Plans and Layout Report for the ESF Thermal Test (CRWMS M&O, 1996n). Rock-mass strength experiments have been deferred until after the viability assessment. The need for this information will be reevaluated for licensing.
8. In the in situ design verification study (8.3.1.15.1.8), geotechnical design verification activities are being conducted in the north ramp and main drift of the ESF to provide data that can be used to confirm adequacy of design, construction, and long-term performance from the beginning of ESF construction. The data from these activities will also be used to support repository design, and to validate the ESF design. The evaluation of mining methods has been limited to collection of rock mass quality data and monitoring of selected drill and blast operations to ensure that damage to the rock mass is limited. Comparison of mining [excavation] methods for repository design and evaluation of controlled blasting will not be done because the repository will be constructed by mechanical excavation. Monitoring of ground support systems is proceeding as planned, as is the monitoring of drift stability. Measurements of radon levels and ventilation studies have been deferred. A small ventilation study was conducted to evaluate the effect of diesel locomotives in the tunnel.

A.1.12.2 Studies to provide the required information for spatial distribution of ambient stress and thermal conditions (SCP Investigation 8.3.1.15.2)

Background and SCP Plans. The objective of this investigation was to determine the spatial variability of ambient stress and in situ temperature to satisfy performance assessment input requirements for geomechanical and thermomechanical models being used for repository design. In addition, heat flow data was to be used, as necessary, as a check on the internal consistency of models of heat and water flow at Yucca Mountain. This investigation includes two studies developed to accomplish the following:

1. Study 8.3.1.15.2.1 (characterization of the site ambient stress conditions): This study was to (a) characterize the ambient (pre-repository) state of stress of the Yucca Mountain host rock and surrounding units for use as initial conditions for geomechanical models used in the design and performance assessment of the repository underground facilities; (b) conduct anelastic strain-recovery experiments on samples from core holes to determine the spatial variability of horizontal stresses at Yucca Mountain; and (c) conduct overcore-stress experiments in the ESF to determine the in situ state of stress above, within, and below the repository host rock and to evaluate the extent to which the ambient stress conditions are redistributed adjacent to excavations.
2. Study 8.3.1.15.2.2 (characterization of the site ambient thermal conditions): This study was to (a) characterize the ambient (pre-repository) temperature of the Yucca Mountain host rock and surrounding units for use as initial conditions for thermomechanical models used in the design and performance assessment of the repository underground facilities; (b) measure the spatial variation of temperature with depth in existing surface-based boreholes and provide baseline temperatures within the repository host rock and surrounding units; (c) measure thermal conductivity (near 25°C) of core samples as a check on independent thermal-property determinations; and (d) determine heat flow at Yucca Mountain.

Changes and Status. The objectives of this investigation have not changed significantly since the SCP was issued. However, changes to the scope of work have been made to consolidate related studies. Some of the changes resulted from the change from a shaft-and-main configuration for the ESF and the potential repository described in the SCP to the ramps and drift configuration now baselined. Other changes resulted from DOE's efforts to reevaluate and prioritize the Project's information needs based on scientific criteria that considered the needs to (1) ensure that data needed for site characterization purposes are collected and analyzed, and (2) eliminate data-collection redundancy and overlap. The data-collection needs have been further analyzed and refined as additional knowledge has been gained through years of site characterization activities. This process has resulted in the following changes to the characterization program.

1. In the study of site ambient stress conditions (8.3.1.15.2.1), much of the work scope was developed to support design and operation of the shaft configuration for the ESF

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and potential repository. The change in the ESF and potential repository configurations to ramps and drifts eliminated the need for anelastic strain-recovery experiments. Further, the work scope associated with the overcore-stress experiments has been transferred to Study 8.3.1.15.1.8, "In Site Design Verification" (see Section 3.11.8 of this progress report). Studies associated with boreholes USW G-1 and USW G-2 are described in Chapter 1 of the SCP. From 1981 to 1985, hydraulic fracturing stress measurements were conducted at depths of 0.3 to 1.7 km in four wells drilled in Yucca Mountain (Stock et al., 1985; Stock and Healy, 1988). The results of recently completed hydraulic fracturing in situ stress measurements in a 30 m deep test hole drilled from the Thermal Test Facility, have shown that the measured horizontal stresses are only moderately differential and are smaller than the vertical stress. The stress regime corresponds to the locally predominant normal faulting, and is in accord with the average strike direction of the normal faults. The hydraulic fracturing data generally corroborates the results of ambient stress measurements made prior to preparation of the SCP. Therefore, the pre-SCP data are considered adequate to support the probabilistic seismic hazard analysis, total system performance assessment, and viability assessment. Additional in situ stress tests will be performed as part of the plate-load tests in the ESF Thermal Testing Facility (see Investigation 8.3.1.15.1).

2. In the study of site ambient thermal conditions (8.3.1.15.2.2), the work scope has been transferred to the closely related SCP Activity 8.3.1.8.5.2.3 (heat flow at Yucca Mountain and evaluation of regional ambient heat-flow anomalies). In addition, the overall objective of this work was changed to emphasize evaluation of available thermal data so that the need for additional data collection could be minimized. In FY 1995, a temperature log was run in borehole USW G-2, and the log indicated that the temperature profile in the unsaturated zone had remained unchanged since 1984 (see Section 3.6.9 of Progress Report #13). This information, along with temperature data from several boreholes instrumented in the unsaturated zone as part of Study 8.3.1.2.2.3 (see Section 3.1.7 of this progress report), indicated that additional thermal-profile data from surfaced-based boreholes probably are not needed. A large number of thermal-conductivity measurements have been made on core samples from surface-based boreholes and the ESF under Activity 8.3.1.15.1.1.3 (see Section 3.11.1 of this progress report).

The locations at which temperature logs of horizontal boreholes will be run has changed since the SCP was written, primarily because of the reconfiguration of the ESF and guidance provided by subsurface observations. The Bow Ridge fault has been tested. More extensive testing of the Ghost Dance fault than that envisioned in the SCP is in progress. Testing of the Drill Hole Wash structure and imbricate zone is not currently planned. Also, resolving the relative importance of liquid versus gas-phase movement in the fault zones is becoming a testing priority, whereas the SCP emphasized parameter estimation.

A.1.13 Preclosure Hydrology Program (SCP Section 8.3.1.16)

The SCP preclosure hydrology program was intended to provide data to address design and performance issues related to potential for flooding, the availability of water for repository construction and operation, and the subsurface hydrologic conditions that might require engineering measures that are either excessively costly or beyond those reasonably available.

The investigations included in the Preclosure Hydrology Program are summarized in the following sections.

A.1.13.1 Flood recurrence intervals and levels at potential locations of surface facilities (SCP Investigation 8.3.1.16.1)

Background and SCP Plans. The objectives of this investigation were to determine the magnitudes and frequencies of major flood events that can potentially occur during the period of repository operation; identify all potential areas of inundation; and determine the quantities and size characteristics of debris transported by flooding. This investigation included one study developed to accomplish the following:

Study 8.3.1.16.1.1 (characterization of flood potential of the Yucca Mountain site): This study was to assess the flood and debris flow hazards at and near the potential repository surface facilities locations to allow adequate design of facilities to prevent or reduce hazards to an acceptable level.

Changes and Status. The objectives of the preclosure hydrology program (8.3.1.16) have not changed significantly since the SCP was issued. These objectives have been largely addressed through studies from the Geohydrology Program (8.3.1.2), and through efforts in support of the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k). All data necessary to address the DOE and NRC performance requirements specified in regulations have been (a) delivered, reported, or forward-referenced to outputs in the Project Integrated Safety Assessment, (b) fulfilled with surrogate information, or (c) rendered unnecessary based on early stages of the investigation and evaluation of performance impacts.

In the study to characterize the flood potential of the Yucca Mountain site (8.3.1.16.1.1), precipitation and runoff data compiled largely through the above studies and data supplied in a National Weather Service report (NWS, 1977), were used to develop several probable maximum flood studies that were conducted by the U.S. Bureau of Reclamation (Bullard, 1991; Blanton, 1992) and the USGS (Glancy, 1994). The results of a conservative analysis of the potential for flooding were reported in the Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion (DOE, 1995k). Estimates of water surface elevations associated with the probable maximum flood were shown to pose little problem of repository flooding.

A.1.13.2 Location of adequate water supplies (SCP Investigation 8.3.1.16.2)

Background and SCP Plans. The objectives of this investigation were (a) to locate an adequate water supply for construction, operation, closure, and decommissioning of a mined geologic disposal system at Yucca Mountain, Nevada, and (b) use the information to assess the suitability of candidate wells for repository water supply through decommissioning of the repository. This investigation included one study developed to accomplish the following:

Study 8.3.1.16.2.1 (location of adequate water supply for construction, operation, closure, and decommissioning of a mined geologic disposal system at Yucca Mountain, Nevada): This study was to (a) assess the cost, feasibility, and adequacy of wells UE-25 J#12 and UE-25 J#13 for use as alternative water supply for a mined geologic disposal system at Yucca Mountain, Nevada. Locate a primary water supply for a mined geologic disposal system at Yucca Mountain, Nevada; (b) locate alternative water supplies for a mined geologic disposal system at Yucca Mountain, Nevada; and (c) identify and evaluate potential effects of repository related withdrawals on the local flow system at Yucca Mountain, Nevada.

Changes and Status. The objectives of this investigation have not changed since the SCP was issued. However, the methods used to collect the information were modified to take advantage of information available from other sources.

In the study to locate an adequate water supply for construction, operation, closure, and decommissioning of a mined geologic disposal system (8.3.1.16.2.1), the process to obtain the water permit for site characterization included holding hearings and collecting depositions regarding issues concerning use of water from wells UE-25 J#12, UE-25 J#13, and USW VH-1. Much data and information regarding water budgets, aquifers, and pumping rates and drawdown were presented by contractors from the USGS, U.S. Park Service, and State of Nevada. A monitoring well (UE-25 JF#3) was installed to monitor any potential impacts to regional water levels by water use from site characterization. Additionally, site and regional water-level monitoring has been a continuous effort and these data are published annually by the USGS.

A.1.13.3 Ground-water conditions within and above the potential host rock (SCP Investigation 8.3.1.16.3)

Background and SCP Plans. The objectives of this investigation were to (a) determine the amount of water inflow to the repository horizon including seasonal variations in inflow rate; (b) determine the existence of perched water and (c) define the locations, depths, thicknesses, and lateral extents, seasonal variations and degrees of saturation of any perched-water zones identified. The characterization of the hydrologic conditions within and above the repository horizon was to be accomplished by studies being performed in support of Investigation 8.3.1.2.2 (studies to provide a description of the unsaturated zone hydrologic system of the site). Although the bases for addressing the investigations are different (repository design versus long-term

performance assessment), the parameters that must be obtained to satisfy both of these investigations are the same. Data on flux, moisture content, and potential influx were to be obtained from the geohydrology program (8.3.1.2). The data collected under the geohydrology program were to be compiled, analyzed, and evaluated under Activity 8.3.1.16.3.1.1, and were to be used to define the moisture conditions at the site that are needed for design. This investigation included one study developed to accomplish the following:

Study 8.3.1.16.3.1 (determination of the preclosure hydrologic conditions of the unsaturated zone at Yucca Mountain, Nevada): This study was to synthesize data from site program geohydrology (8.3.1.2), to determine the preclosure hydrologic characteristics of the unsaturated zone at Yucca Mountain, Nevada.

Changes and Status. The objectives of this investigation have not changed since the SCP was issued. The data collection efforts were performed under the geohydrology program as described in the SCP. However, the data evaluation efforts were also largely completed under the geohydrology program to avoid having separate and redundant evaluations performed under Investigation 8.3.1.16.3.

The objectives of the study to determine the preclosure hydrologic conditions of the unsaturated zone at Yucca Mountain, Nevada (8.3.1.16.3.1) are being accomplished according to the description in the SCP. The data needed for this investigation are being collected mostly under the geohydrology program, but some data is being compiled, analyzed, and evaluated under this study. The characterization of the hydrologic conditions within and above the repository horizon is being accomplished by studies being performed in support of Investigation 8.3.1.2.2 (studies to provide a description of the unsaturated zone hydrologic system at the site). Data on flux, moisture content, and potential influx are being obtained from the geohydrology program. Information obtained from new and existing boreholes is providing data concerning perched water, zones of saturation, and many other parameters of concern for unsaturated zone characterization.

A.1.14 Preclosure Tectonics Program (SCP Section 8.3.1.17)

The SCP preclosure tectonics program was a comprehensive, multidisciplined program intended to characterize the tectonic events and processes that could impact proposed repository structures, systems, or components considered to be important to safety until permanent closure is achieved. The purpose of the program was to provide characterizations of tectonic processes and events for consideration in the design and operation of certain structures, systems, and components required for exercising the retrieval option. The program described in the SCP was intended to investigate the tectonic characteristics of the site in sufficient scope and detail to provide reasonable assurance that the processes were understood and that the characterization parameters were determined with the confidences needed to support license application requirements. Information was to be provided from a variety of sources and methods including scientific literature, current and historical seismicity data, geologic maps, logs from boreholes

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and surface trenches, gravity surveys, aeromagnetic and paleomagnetic observations, seismic reflection and refraction profiles, and magnetotelluric soundings.

The investigations included in the preclosure tectonics program are summarized in the following sections.

A.1.14.1 Studies to provide required information on volcanic activity that could affect repository design or performance (SCP Investigation 8.3.1.17.1)

Background and SCP Plans. The objectives of this investigation were to identify and evaluate credible volcanic hazards that could affect preclosure repository performance: (a) ash falls from distal silicic volcanic centers in the western Great Basin, and (b) basaltic volcanic eruptions at the site. The potential for silicic ash falls at the site was studied under this investigation, and the potential for basaltic eruptions was studied under the postclosure tectonics program (8.3.1.8). This investigation included one study developed to accomplish the following:

Study 8.3.1.17.1.1 (potential for ash fall at the site): This study was to (a) compile information on Quaternary silicic volcanism in the western Great Basin, the recurrence of which might produce an ash fall at the site; (b) produce an approximate probability-versus-thickness function for potential ash falls at the site and estimate a particular ash fall thickness that has less than one chance in ten of occurring in 100 years; and (c) estimate the potential particle densities and particle-size distributions of ash falls at the site to support design of ventilation filters.

Changes and Status. The primary objectives of this investigation have not changed. The work described in the SCP was accomplished by compiling and evaluating information on silicic volcanism in the western United States (Perry and Crowe, 1987; DOE, 1996k). No additional work is planned.

A.1.14.2 Provide information on fault displacement that could affect repository design or performance (SCP Investigation 8.3.1.17.2)

Background and SCP Plans. This investigation was intended to provide information that could be used to avoid siting of facilities or waste packages in areas with potential for fault displacements in excess of a few inches. The siting objective for surface faulting was to avoid fault displacement in excess of a few inches beneath the structural foundations of surface facilities considered important to safety. The primary concern regarding faulting in the underground facilities during preclosure was that waste packages might be sheared or become jammed in their waste-emplacement boreholes, making retrieval more difficult and time consuming than it otherwise might be. No single fault with the potential to create such problems was thought to exist, but if such a fault were identified, an attempt would be made to determine its location underground for consideration in the positioning of waste-emplacement boreholes. This investigation included one study developed to accomplish the following:

Study 8.3.1.17.2.1 (faulting potential at the repository): This study was to (a) assess the stability of the site surface with respect to fault displacement at locations proposed for facilities important to safety and demonstrate, with a high degree of confidence, that there is less than a one percent chance of exceeding 5 cm of fault displacement beneath surface facilities important to safety during the preclosure period (approximately 100 years); and (b) assess the potential for displacement on faults that intersect underground facilities and demonstrate, with a moderate degree of confidence, that there is less than a 10 percent chance of exceeding 7 cm of fault displacement in areas of emplaced waste in 100 years, considering all faults that may intersect these areas.

Changes and Status. The objectives of this investigation have not changed since the SCP was issued. However, the work scope for this investigation and study has been combined with Study 8.3.1.17.3.6 (probabilistic seismic hazards analyses) under Investigation 8.3.1.17.3 (Section A.1.14.3).

A.1.14.3 Provide information on vibratory ground motion that could affect repository design or performance (SCP Investigation 8.3.1.17.3)

Background and SCP Plans. The purposes of this investigation were to develop a seismic-design basis for repository facilities that were important to safety and provide other information that would facilitate the assessment of the adequacy of the seismic-design basis and the identification of credible accidents that might be initiated by seismic events and lead to release of radioactive materials. The seismic-design basis will account for both the potential occurrence of earthquakes on nearby faults and potential future underground nuclear explosions at the Nevada Test Site. The investigation describes the analyses required to develop the seismic design basis for repository facilities important to safety, both surface and underground, and a deterministic methodology proposed for evaluation of seismic hazards. This methodology included 10,000-year cumulative slip earthquake methodology for establishing earthquake magnitudes for use in estimating design ground motions. As originally proposed in the SCP, this did not include evaluation of fault-displacement hazards. This investigation included six studies developed to accomplish the following:

1. Study 8.3.1.17.3.1 (relevant earthquake sources): This study was to (a) identify and characterize those earthquake sources that were relevant to a deterministic seismic hazard analysis of the site including faults with surface geologic expression as well as concealed faults; (b) identify earthquake sources that could generate severe ground motions at the site; and (c) characterize 10,000-year cumulative slip earthquakes for each of the relevant seismogenic sources identified.
2. Study 8.3.1.17.3.2 (underground nuclear explosion sources): This study was to characterize the potential future underground nuclear explosions at the Nevada Test Site that would result in the most severe motions at the repository site.

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3. Study 8.3.1.17.3.3 (ground motion from regional earthquakes and underground nuclear explosions): This study was to select or develop ground-motion models that were appropriate for estimating ground motion at the site from regional earthquakes and underground nuclear explosions.
4. Study 8.3.1.17.3.4 (effects of local site geology on surface and subsurface motions): This study was to (a) document systematic effects on surface and subsurface ground motions resulting from the local site geology based on instrumental recordings of ground motion at the site; (b) identify any significant site-wide bias in ground-motion levels as compared with average levels for the southern Great Basin; and (c) develop a calibrated theoretical site-effects model using the wave properties of the local geology to extrapolate the effects to locations and depths where ground-motion recordings were not available.
5. Study 8.3.1.17.3.5 (ground motion at the site from controlling seismic events): This study was to identify the controlling seismic events (underground nuclear explosions or 10,000-year cumulative slip earthquakes that would generate the most severe ground motions at the site at frequencies of engineering significance) and characterize the resulting controlling ground motions generating suites of strong-motion time histories and corresponding response spectra that were representative in amplitude, frequency content, and duration of site ground motions.
6. Study 8.3.1.17.3.6 (probabilistic seismic hazard analysis): This study was to (a) quantify the probability for experiencing ground motions of varying degrees of severity that might result from earthquakes of varying magnitude and distance from the site and use these results to constrain required technical judgments in the deterministic evaluation of design-basis ground motions, evaluate the adequacy of the deterministic results, and help focus efforts to refine those parameters that were most important for the deterministic calculations; (b) determine average rates for earthquake recurrence as a function of magnitude for the southern Great Basin to a distance of about 100 km from the site and then apportion these rates onto active faults and subregional seismic source zones; and (c) estimate the probability of exceeding given ground-motion levels at the site and integrate the contributions to the probability from all identified earthquake sources that could generate potentially damaging ground motion at the site.

Changes and Status. The primary objective of the investigation has not changed since the SCP was issued. However, significant changes in approach and methodology have occurred. These are summarized below.

1. In the study of relevant earthquake sources (8.3.1.17.3.1), the 10,000-year cumulative slip earthquake approach and the deterministic methodology have been abandoned. Instead, a probabilistic seismic hazard analysis is being used for developing the seismic-design basis for both ground motion and fault displacement. This methodology is described in two DOE-YMSCO topical reports (DOE, 1994b and 1995b). All work identified in the SCP to compile relevant earthquake sources for use

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- in the probabilistic seismic hazard analysis and to develop attenuation relations for underground nuclear explosions and earthquakes has been completed.
2. In the study of underground nuclear explosion sources (8.3.1.17.3.2), only a preliminary assessment of potential locations and yields of underground nuclear explosions has been completed. There are, however, no further plans to characterize the potential future occurrence of underground nuclear explosions because no additional underground testing is expected in the foreseeable future.
 3. In the study of ground motion from regional earthquakes and underground nuclear explosions (8.3.1.17.3.3), selection and development of ground-motion models has proceeded largely as described in the SCP. Simulations have been completed with multiple, numerical ground-motion models using a suite of deterministic "scenario earthquakes" and newly developed empirical ground-motion attenuation models for normal-fault earthquakes using a world-wide data set. In addition, a ground-motion attenuation model for underground nuclear explosions using site-specific data collected from surface and subsurface stations at Yucca Mountain has been completed.
 4. In the study of effects of local site geology on surface and subsurface motions (8.3.1.17.3.4), direct documentation of ground-motion effects has benefitted from recordings made at seismograph stations on bedrock sites on and near Yucca Mountain of the largest after shocks of the $M_L = 5.6$ Little Skull Mountain earthquake of 1992. Shallow velocity profiles have been used to derive in situ seismic velocities at the potential repository site.
 5. In the study of ground motion at the site from controlling seismic events (8.3.1.17.3.5), the objectives of this study are expected to be achieved by applying the results of the probabilistic seismic hazard analyses being conducted in Study 8.3.1.17.3.6. Note, however, that the concept of the 10,000-year cumulative slip earthquake is not being used.
 6. In the probabilistic seismic hazard analysis (8.3.1.17.3.6), the study has been expanded to include evaluation of the potential for fault displacement, which originally was to have been conducted under Study 8.3.1.17.2.1 (faulting potential at the repository). In addition, the 10,000-year cumulative slip earthquake approach and the deterministic methodology have been abandoned. Instead a probabilistic seismic hazard analysis is being used for developing the seismic design basis for both ground motion and fault displacement. This methodology is described in two DOE-YMSCO topical reports (DOE, 1994b and 1995b). As discussed in those reports, the preferred methodology for seismic hazard analyses includes an elicitation process whereby a panel of experts is assembled to interpret the available seismological, geological, geophysical, and geotechnical data sets and, through a series of workshops, provide probability estimates for the occurrence of ground motions or fault displacements of sufficient magnitudes to affect repository design and performance.

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A.1.14.4 Preclosure tectonics data collection and analysis (SCP Investigation 8.3.1.17.4)

Background and SCP Plans. The primary purpose of this investigation was to provide the data and analyses required to assess fault displacement that could affect repository design or performance (Investigation 8.3.1.17.2) and assess vibratory ground motion that could affect repository design or performance (Investigation 8.3.1.17.3). The primary focus was the compilation and analysis of information on reported and instrumentally recorded earthquakes that have occurred near Yucca Mountain. The data are needed to develop the technical basis for fault displacement and ground-motion hazards and the preclosure seismic design bases for surface and subsurface facilities. Testing proposed in the SCP included a wide range of activities comparable to site-specific seismic hazard studies for other critical facilities. These included collection of fault-specific paleoseismic data from trenching, monitoring, and analysis of historical and current seismicity; geophysical surveys; downhole and underground measurements of the in situ stress field; geodetic leveling; and tectonic modeling. The limited data collection and analysis that is required by Investigation 8.3.1.17.1 (volcanic activity that could impact the repository) will be performed within that investigation. This investigation included 12 studies developed to accomplish the following:

1. Study 8.3.1.17.4.1 (historical and current seismicity): This study was to (a) compile information on reported and instrumentally recorded earthquakes that characterize the earthquake potential near Yucca Mountain; (b) compile a record of historical seismic events in the southern Great Basin or within 100 km of Yucca Mountain, including type of event, ground-motion intensity for potentially damaging earthquakes, and extent and style of faulting; (c) monitor current seismicity to provide empirical information on the current frequency of earthquakes in the southern Great Basin, characteristics of faulting, how seismic wave amplitudes scale with magnitude and attenuate with distance in the region, and how ground motions vary with depth and with surface geology in the site area; and (d) evaluate the potential for human activities to significantly perturb the natural seismic hazard at the site by inducing seismicity at or near the site.
2. Study 8.3.1.17.4.2 (location and recency of faulting near prospective surface facilities): This study was to (a) identify appropriate trench locations in Midway Valley at proposed locations for repository surface facilities that are important to safety through detailed geologic mapping and remote sensing studies; and (b) conduct exploratory trenching in Midway Valley to investigate possible occurrences of late-Quaternary surface-fault rupture in the vicinity of planned surface facility locations important to safety and to identify sites without evidence of significant late-Quaternary faulting.
3. Study 8.3.1.17.4.3 (Quaternary faulting within 100 km of Yucca Mountain, including the Walker Lane): This study was to (a) identify Quaternary faults within 100 km of Yucca Mountain and characterize those faults capable of future earthquakes that could impact design or affect performance of the waste facility; (b) conduct and evaluate deep geophysical surveys in an east-west transect crossing the Furnace Creek fault zone, Yucca Mountain, and the Walker Lane to help identify and locate potentially

significant seismic source zones including possible through-going extensions of the Walker Lane and the Furnace Creek fault zone and the relation of these features to detachment faults and to Quaternary faults; evaluate the postulated incipient rift zone at Crater Flat; (c) compare results of seismic-reflection surveys with result of magneto-telluric surveys; (d) characterize the conductivity structure of the crust in the Yucca Mountain region; provide data for analysis to determine if buried magma bodies are present in the vicinity of Yucca Mountain; (e) characterize the Quaternary and Holocene fault and fracture pattern within 100 km of the site and relate that pattern to wrench fault systems, including the Walker Lane, the Death Valley-Furnace Creek fault zone, and the Mine Mountain-Pahranagat shear zone; (f) determine whether the Beatty scarp originated through tectonic or fluvial processes, the nature of movement along the scarp (if tectonic), and the age of the scarp; (g) ascertain the amount of post-middle Miocene horizontal rotation of bedrock alongside wrench faults and of bedrock suspected to be part of the upper plate above subsurface wrench faults; (h) evaluate the Cedar Mountain earthquake of 1932 and its relevance to wrench tectonics of the Walker Lane and to potential sources of ground shaking and rupture within 100 km of the site; (i) evaluate the potential for ground shaking associated with future movement along the Bare Mountain fault zone, estimate the age of the most recent faulting and the recurrence intervals of faulting on the Bare Mountain frontal fault, and determine the nature and age of faulting within the fault complex east of the frontal zone; (j) evaluate structural domains and characterize the Yucca Mountain region with respect to regional patterns of faults and fractures; (k) classify the area into subareas (domains) containing relatively homogeneous fault and lineament populations suggestive of Quaternary faulting; (l) map the areal extent of desert varnish coatings; and (m) identify areas of suspected hydrothermal alteration.

4. Study 8.3.1.17.4.4 (Quaternary faulting proximal to the site within northeast-trending fault zones): This study was to (a) evaluate the potential for ground motion resulting from future movement on Quaternary left-lateral strike-slip faults within northeast-trending fault zones east and south of the site-area; and (b) determine the location, spatial orientation, length, width, Quaternary recurrence rate, and the location, amount, and nature of Quaternary movement of the Rock Valley, Mine Mountain, Stagecoach Road, and Cane Spring fault systems.
5. Study 8.3.1.17.4.5 (detachment faults at or proximal to Yucca Mountain): This study was to (a) supply information pertaining to the distribution, displacement rate, and age of detachment faults proximal to Yucca Mountain to determine whether they represent a significant earthquake source and whether they conceal a significant earthquake source at depth; (b) evaluate the significance of the Miocene-Paleozoic contact in the Calico Hills area to detachment faulting and to determine whether the contact of Miocene volcanic rocks on Paleozoic strata is tectonic or depositional; (c) evaluate postulated detachment faults in the Beatty-Bare Mountain area and determine if these have been active in the Quaternary; (d) evaluate the potential relationship of breccia within and south of Crater Flat to detachment faulting; (e) evaluate postulated detachment faults in the Specter Range and Camp Desert Rock areas and determine

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whether the basal contact of the Horse Spring Formation is depositional or tectonic and if movement has occurred in the Quaternary; and (f) evaluate the age of detachment faults using radiometric ages.

6. Study 8.3.1.17.4.6 (Quaternary faulting within the site area): This study was to (a) identify and characterize Quaternary faults that intersect or project toward the surface facility, the repository, or the controlled area and determine the potential for future earthquakes that could impact design or affect performance of the waste facility; (b) synthesize data pertaining to the location, spatial orientation, length, width, Quaternary recurrence rate, and the location, amount, and nature of Quaternary movement of faults within the site area; (c) identify hitherto unrecognized Quaternary faults; and (d) evaluate age and recurrence of movement on suspected and known Quaternary faults including the Paintbrush Canyon, Solitario Canyon, Windy Wash, Ghost Dance, and Bow Ridge faults.
7. Study 8.3.1.17.4.7 (subsurface geometry and concealed extensions of Quaternary faults at Yucca Mountain): This study was to evaluate the subsurface geometry and concealed extensions of Quaternary faults at Yucca Mountain using the following methods: intermediate seismic refraction and reflection, detailed gravity surveys, detailed aeromagnetic surveys, ground magnetic surveys, surface geoelectric, gamma-ray measurements, thermal infrared, and shallow seismic-reflection (mini-sosie) methods.
8. Study 8.3.1.17.4.8 (stress field within and proximal to the site area): This study was to (a) provide data on the ambient stress field at the site and its immediate vicinity that will aid in evaluating future movement on faults, stability of potential pathways for radionuclide travel controlled by or related to fracture aperture, stability of mined excavations, response of the rock mass to thermal loading, and applicability of tectonic models; (b) measure vertical and lateral variations of in situ stress at the site including in the vicinity of the steep hydraulic gradient and at the postulated detachment fault and in subjacent Paleozoic rocks below Yucca Mountain; (c) evaluate and test shallow borehole hydrofracture and triaxial strain recovery methods for the determination of in situ stress; (d) evaluate published and unpublished data on paleostress orientation at and proximal to the site and assess the relevance of these data to Quaternary tectonics; (e) evaluate theoretical stress distributions associated with potential tectonic settings of Yucca Mountain including wrench-fault, normal-fault, and detachment-fault tectonic models; (f) evaluate the degree to which in situ stress data constrain applicability of these tectonic models to neotectonics of the site; and (g) evaluate the potential relation between fracture aperture and in situ stress.
9. Study 8.3.1.17.4.9 (tectonic geomorphology of the Yucca Mountain region): This study was to (a) conduct studies of tectonic geomorphology in the Yucca Mountain region to document the magnitude of Quaternary uplift and subsidence and to evaluate regional variation in the nature and intensity of Quaternary faulting; (b) evaluate the age and areal distribution of surfaces that appear to have been tectonically stable at and

near Yucca Mountain through studies of desert varnish; (c) evaluate extent of areas of Quaternary uplift and subsidence at and near Yucca Mountain through evaluation of fluvial fans in the Amargosa Desert, Crater Flat, Fortymile Wash, Rock Valley, and Ash Meadows; and (d) evaluate variations in the nature and intensity of Quaternary faulting within 100 km of Yucca Mountain through morphometric and morphologic analysis.

10. Study 8.3.1.17.4.10 (geodetic leveling): This study was to (a) conduct geodetic releveling of base stations and benchmarks to evaluate possible historical and contemporary vertical displacements across potentially significant Quaternary faults within 100 km of Yucca Mountain and to characterize the historical rate of uplift and subsidence; and (b) survey selected base stations near Yucca Mountain using global positioning satellite.
11. Study 8.3.1.17.4.11 (characterization of regional lateral crustal movement: This study was to evaluate rates and orientations of historical and current lateral crustal movement in the Basin and Range province and the Yucca Mountain region using analyses of existing data on seismicity, historical fault offset, and creep.
12. Study 8.3.1.17.4.12 (tectonic models and synthesis): This study was to (a) conduct tectonic modeling and synthesis to evaluate all data relevant to tectonics at Yucca Mountain; (b) develop a model or range of models that establishes the causal relation between application of tectonic forces and formation of structures (wrench, detachment, normal, and left-lateral strike-slip faulting, oroclinal bending, etc.) observed at Yucca Mountain and vicinity; (c) link observed rates of formation of those structures with regional rates of crustal strain; (d) forecast changes in tectonic setting and the manner in which those changes will affect both the regional crustal strain rate and tectonic stability in the Yucca Mountain region; (e) estimate the effect of those changes on rate and nature of crustal strain at Yucca Mountain and vicinity; (f) estimate the future rate of tectonic processes at Yucca Mountain and evaluate the applicability of this information to geologic hazards at the site; and (g) evaluate tectonic disruption sequences involving faulting, folding, uplift and subsidence, and volcanism that are potentially significant to design or performance of the repository.

Changes and Status. The objectives of this investigation have not changed since the SCP was issued. Sufficient data have been collected in Investigation 8.3.1.17.4 to form an adequate technical basis for proceeding with the seismic hazard analysis. The seismic-hazard characterization program has focused on characterizing Quaternary faults at and near Yucca Mountain through trench excavation, mapping, and analysis in order to constrain the Quaternary history of faulting and earthquakes. Multiple trenches have been excavated across each of the known or suspected Quaternary faults in the site area and on the most active Quaternary faults in the region. Trench interpretations, slip-rate and recurrence analyses, and fault-displacement and length analyses are nearly complete. A catalog of historical earthquakes has been prepared. Information from monitoring the Little Skull Mountain earthquake in 1992 and continuing after shocks has greatly increased understanding of the characteristics of moderate-magnitude

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earthquakes. In situ stress and geodetic-leveling data have been compiled and analyzed. Alternate tectonic models constrained by available geologic mapping and geophysical surveys have been formulated. Although the overall objectives of the SCP have been met, some changes in scope and strategy have occurred since the SCP was issued. These changes are summarized below.

1. In the study of historical and current seismicity (8.3.1.17.4.1), the compilation of historical seismic events was expanded to include those events that occurred within a 300-km radius rather than the originally designated 100-km radius. This modification in scope was in response to discussions with the NRC. In the monitoring of current seismicity, the southern Great Basin seismic network has been upgraded to provide more precise information for the Yucca Mountain area. Whereas the original seismic network consisted of 49 analog seismograph stations within a 150-km radius of Yucca Mountain, the upgraded network will consist of 27 digital stations within a 50-km radius, 23 of which have been installed (see Section 3.13.9 of this progress report). The upgraded southern Great Basin seismic network is significantly more sensitive than the original network, and this enhanced sensitivity has enabled detection of ESF excavation-induced seismicity. The upgraded network has 9 strong-motion stations at Yucca Mountain, whereas the SCP expected about 6. Finally, continuous monitoring of two seismometers installed in borehole UE-25 UZ#16 is being conducted.
2. In the study of location and recency of faulting near prospective surface facilities (8.3.1.17.4.2), all SCP objectives have been achieved without significant change in scope. Faults demonstrating Quaternary activity were identified, but none of these are located in the immediate vicinity of prospective surface facilities or the potential repository. No further work is planned for this study.
3. In the study of Quaternary faulting within 100 km of Yucca Mountain (8.3.1.17.4.3), some of the principal objectives were not met for various reasons, including (a) the work was performed in another study, and (b) the expected results would not justify the resources needed to obtain the information based on previous results. The Project has embarked on an expert elicitation to evaluate the probability and effects of possible seismic and tectonic events. This elicitation will use a wide range of data and experience to appropriately bound the reasonable range in initiating events and intensities. These bounds will be incorporated in analyses of both preclosure and postclosure performance assessment. Significant changes in scope from that outlined in the SCP are as follows:
 - Seismic reflection surveys were limited to a 37-km-long traverse extending eastward from the east flank of Bare Mountain across Crater Flat to the east side of Yucca Mountain (results reported in Study 8.3.1.4.2.1, Section 3.3.3 of this progress report). No surveys were conducted across the Furnace Creek fault zone. Geologic field studies, however, were conducted along the Death Valley-Furnace Creek fault zones to characterize the style of faulting and to determine the history and magnitude of fault displacements.

- No new magneto-telluric surveys were made to supplement earlier surveys across parts of the Yucca Mountain area. Although magneto-telluric data can be expected to provide certain constraints on crustal structure and composition, final interpretations of the data require integration with coincident data from deep seismic profiles, teleseismic data, heat-flow and Curie isotherm determinations, and gravity measurements. The personnel requirements and cost of additional magneto-telluric surveys were considered to be too high when compared with the expected results in terms of providing quantitative data that would significantly augment other geological and geophysical data sets being used to interpret Yucca Mountain structure.
 - The Cedar Mountain earthquake and its potential as a source for producing future ground shaking at the Yucca Mountain site are being evaluated in Study 8.3.1.17.3.6 (probabilistic seismic hazard analysis) as part of the effort involved in probabilistic seismic hazards analysis.
 - Structural domains and regional patterns of faults and fractures are being evaluated as part of Study 8.3.1.17.4.12. The latter study is also classifying the Yucca Mountain area into subareas containing relatively homogeneous fault and lineament populations.
 - Desert-varnish coatings are not being mapped as part of Study 8.3.1.17.4.3, but their general distribution is being provided through the mapping of surficial deposits as part of Activity 8.3.1.5.1.4.2 (see Section 3.4.4 of this progress report). Desert-varnish coatings in the immediate vicinity of Yucca Mountain also were described in Whitney and Harrington (1993).
 - Hydrothermal alteration has not been a subject of study in 8.3.1.17.4.3. Altered rocks in the Calico Hills area were mapped as part of Study 8.3.1.17.4.5, and alteration zones are also being described based on outcrop observations and core examinations being made in Study 8.3.1.4.2.1 (see Section 3.3.3 of this progress report).
4. In the study of Quaternary faulting proximal to the site within northeast-trending fault zones (8.3.1.17.4.4), all SCP objectives have been met, including characterization of the Stagecoach Road fault, which was studied as part of Study 8.3.1.17.4.6. No further work is planned for this study.
 5. In the study of detachment faults at or proximal to Yucca Mountain (8.3.1.17.4.5), all SCP objectives have been achieved without significant changes in scope. Importantly, the Paleozoic-Tertiary contact appears to be an unconformity rather than an active detachment surface (see Section 3.13.13 of this progress report). No further work is planned for this study.

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6. In the study of Quaternary faulting within the site area (8.3.1.17.4.6), all SCP objectives are being met, with the Stagecoach Road fault added to the number of individual faults that were trenched and mapped in detail.
7. In the study of subsurface geometry and concealed extensions of Quaternary faults at Yucca Mountain (8.3.1.17.4.7), the SCP objectives are being achieved in other site-characterization studies as discussed in Section 3.13.15 of this progress report. Geophysical surveys are being performed in Study 8.3.1.4.2.1 (see Section 3.3.3 of this progress report), and the data are being used to interpret fault geometries at depth. The resulting interpretations are being applied in the probabilistic analyses of seismic hazards at the potential repository site (Study 8.3.1.17.3.6, Section 3.13.8 of this progress report).
8. In the study of the stress field within and proximal to the site area (8.3.1.17.4.8), a study plan was prepared but has not been finalized. The planned work primarily involves measurements of the vertical and lateral variations of in situ stress in new boreholes that would have to be drilled in the immediate vicinity of the potential repository site. The drilling of these boreholes, however, is not part of the long-range plan. Several of the principal objectives of the study, however, are being met in other studies, most notably in Study 8.3.1.17.4.12, the scope of investigation of which includes evaluating (a) data on paleostress orientation at and proximal to the site and the relevance of these data to Quaternary tectonics, and (b) theoretical stress distributions with potential tectonic settings of the site. Crustal-stress orientations also are considered in probabilistic seismic-hazard analyses (Study 8.3.1.17.3.6). Note that a large number of publications describe crustal stresses in the southwestern United States, including some close to Yucca Mountain (e.g., Stock et al., 1985).
9. In the study of tectonic geomorphology of the Yucca Mountain region (8.3.1.17.4.9), the SCP objectives are being met in other studies as discussed in Section 3.13.17 of this progress report. Quaternary deposits are being mapped in Study 8.3.1.5.1.4 (see Section 3.4.4 of this progress report), with particular emphasis given to alluvial fan deposits in Fortymile Wash and their significance for interpreting the Quaternary history of the area. Data on the nature and intensity of Quaternary faulting within 100 km of Yucca Mountain are being collected in Studies 8.3.1.17.4.3 and 8.3.1.17.4.6, including the geomorphic expression of features marking fault alignments and scarps. The relevance of using desert-varnish coatings for evaluating slope stability in the immediate site area during the Quaternary was discussed in Whitney and Harrington (1993). No further work is planned for this study.
10. In the geodetic-leveling study (8.3.1.17.4.10), all SCP objectives are being met. In addition to monitoring contemporary vertical displacements across Quaternary faults, lateral crustal strain is being measured by a regional network of Global Positioning System stations and by methods involving very long baseline interferometry. This study of the lateral crustal strain was transferred from Study 8.3.1.17.4.11. Most of the study has been completed, but additional resurveys of level lines and Global

Positioning System recordings along established traverses will be made contingent upon availability of funding.

11. In the characterization of regional lateral crustal movement (8.3.1.17.4.11), the SCP objectives are being achieved primarily in Study 8.3.1.17.4.10, and the data are being applied extensively in Study 8.3.1.17.4.12.
12. In the tectonic models and synthesis study (8.3.1.17.4.12), all SCP objectives are being met, with the exception of the evaluation of tectonic disruption sequences. This objective is being addressed in further work being planned in Study 8.3.1.8.2.1 (see Section 3.6.3 of this progress report).

A.1.15 Altered Zone Characterization

Altered zone characterization was not included in the SCP; rather it was developed after the SCP was issued and initiated to provide data on the area surrounding the immediate repository emplacement area. The altered zone characterization consists of a single study that includes four activities. Unlike previous sections, this section presents a summary at the study level rather than the investigation level; individual activities, however, are not summarized as numbered items.

The altered zone is generally considered to be the volume of rock that surrounds the near-field environment (emplacement area) and is defined as that part of the natural system that is likely to experience fundamental changes to hydrological, mineralogical, or chemical conditions because of reactions caused by heating of the repository block from radioactive decay of emplaced nuclear waste. The altered zone is distinguished from the near-field environment on the basis of processes that are expected to dominate. In the altered zone, hydrologic processes are expected to be dominated by increased water availability and increased saturation. The increased moisture content is expected to be produced by vapor condensation at the margins of the near-field environment. Temperatures in the altered zone are expected to be elevated several tens of degrees centigrade relative to ambient conditions. Geochemical processes are expected to be dominated by fluid-rock interactions and reactive transport. The altered zone is expected to be less dynamic than the near-field environment in that the residence times for water are expected to be longer and the dryout zone is not expected to feature zones of condensation at the margins of the near-field environment. The fluid-rock interactions are expected to result in significant coupling between hydrological and geochemical processes, such that fluid pathways and geochemical conditions will evolve in a synergistic way.

Generally, the altered zone will be considered to be the regions surrounding the emplacement areas that maintain temperatures sufficiently low to allow liquid water to exist in pores and fractures. This distinction has the advantage of focusing attention on the dominant processes that may affect performance in different regions of the repository (e.g., evaporation of water and mineral dehydration in the near-field environment (generally surrounded by a region

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dominated by water-rock interactions) and the kinetics of dissolution and precipitation in the altered zone).

As a result of work reported in the Preliminary Near-Field Environment Report (Wukder, 1993) which focused on the environmental conditions that directly impact the waste package container materials and the waste form, those same processes or interactions were recognized as potential causes of significant or changes in fundamental properties that could extend for considerable distances into the rock mass or natural system. Therefore, a zone termed the altered zone was defined and a study was developed to characterize this region wherein fundamental changes to hydrologic, mineralogical, or chemical conditions may take place within the natural system, but where these conditions do not interact directly with the waste packages (rather interact with the near-field environment) and where the changes are more significant than in the far-field environment where ambient conditions tend to prevail. Study Plan 8.3.1.20.1.1, "Characterization of the Altered Zone," was developed to document this work and a draft (dated January 1995) was submitted to the DOE for approval.

A.1.15.1 Altered Zone Characterization (SCP Study 8.3.1.20.1.1)

Background and Plans. The objectives of this study were (a) to evaluate the impact of chemical, mineralogical, and mechanical changes on hydrological properties and determine the kinetics of the change processes; (b) compare computer codes and evaluate their suitabilities for application to altered zone evaluations; (c) determine parameter values, limits, or ranges needed to define the waste package (near-field) environment; and (d) determine, using simulations, the expected response of the altered zone over time. Four activities were included in this study.

Changes and Status. Study Plan 8.3.1.20.1.1 has been reviewed and revised, and no significant changes resulted. Concurrence with the revisions and approval of the revised study plan is expected in FY 1997.

A.2 REPOSITORY PROGRAM (SCP SECTION 8.3.2)

A.2.1 Introduction

As envisioned in the SCP, the repository was to consist of thin-wall waste packages that would be emplaced in boreholes drilled in the floors or walls of emplacement drifts. However, since the SCP was written, this repository design concept has changed substantially, in part because of DOE goals for earlier waste acceptance. Current plans are to emplace large, robust waste packages in drifts. The emplacement of waste packages in drifts is expected to have significant performance and cost advantages over borehole emplacement. First, drift emplacement would allow the packages to radiate heat to a larger area and thus would help control maximum temperatures. Second, a severe seismic event with shear displacements in the repository horizon would be less likely to damage drift-emplaced waste containers. Third, drift emplacement would simplify emplacement operations by eliminating the need to drill boreholes and emplace waste packages in them. Finally, boreholes appear to have a greater tendency to accumulate ground water and to confine the products of degradation.

The repository design concept in the SCP would have interfaced with the excavations planned for the ESF. However, since the SCP was written, both the repository and ESF concepts have changed. The current repository design is integrated with the drift-based approach under which the ESF was actually constructed. Access to the proposed repository is expected to be via a more gently sloped ramp than was envisioned in the SCP. This concept is consistent with the change to large waste packages and would allow use of the ESF north ramp already completed.

Another change that has occurred is that the design is no longer planned to be documented in a license application design report. Instead, the information that it would have contained will be an integral part of the license application documentation.

Although repository design has substantially changed from that described in the SCP, most of the approaches and types of technical information identified in the SCP to support the design are still consistent with the current Program approach.

The status of the repository design activities discussed in the SCP is discussed in more detail in the following sections.

A.2.2 Summary of Changes in the Repository Program

This section discusses in order each section contained in Section 8.3.2 of the SCP—the section that outlined the repository program. First, appropriate background is provided and SCP plans are given. Then the changes that have occurred since the SCP was written are discussed and the current Project status outlined. In this discussion, references to sections, tables, and figures are to the SCP unless otherwise stated.

Overview of repository program (SCP Section 8.3.2.1)

Background and SCP Plans. This SCP section served as the introduction for the description of the repository program and introduced the four repository design issues to be discussed. In addition, the section provided details on the interrelationships of the issues, the manner in which duplication of effort would be avoided, and the approach to ensuring issue resolutions were appropriately integrated. The second major component of this section was a description of the major phases of the repository design from the completed conceptual design (described in Section 6 of the SCP) through final procurement and construction design.

Changes and Status. The issues discussed in this section (and throughout the SCP) are, overall, still applicable, and the program is working toward closing them. However, the designations of the issues and subissues used in the SCP are not generally being used. In other words, although "Configuration of underground facilities" is still a subject being addressed by the Program, it is not commonly referred to as "Issue 1.11." The phases of design described in this section are still generally applicable. The current design to support the 1998 viability assessment, though not discussed in the SCP, fits within the period close to the end of advanced conceptual design and the beginning of license application design. There will be no license application design report; instead the information that it would contain will be an integral part of the license application documentation. The terms "Title I" and "Title II" have been dropped from Project use because of the overlapping of meanings between them and the work scopes of the design phases. The names of the design phases are now used to define work scopes. For example, drawings and specifications released for bidding are now referred to as bid documents, regardless of how many are released at one time. Partial releases are no longer referred to as bid packages. Another change is the use of a Management and Operating Contractor to develop the design, as opposed to a "System Engineering Development and Management" contractor.

Verification or measurement of host-rock environment (Section 8.3.2.1.1)

Background and SCP Plans. This section introduced and discussed the development of models for the understanding of the site host-rock conditions for three distinct phases: before excavation; after excavation but before waste emplacement; and after waste emplacement. The section introduced three following subsections, each covering one of the above phases.

Changes and Status. Understanding of the site host rock is still an important part of the repository program. The program is still focused on developing an understanding of the reaction of the host rock to both excavation and waste emplacement.

Pre-waste-emplacement environment (SCP Section 8.3.2.1.1.1)

Background and SCP Plans. This section described 15 activities required to characterize the site in its undisturbed, initial condition. Listed are 5 additional site data requirements needed for seismic evaluations. The various site programs through which the data would be acquired were noted.

Changes and Status. All items are still applicable to repository design. Data acquisition in these areas continues. The development of the ESF has provided, and continues to provide, much of the information listed.

Post-subsurface-excavation environment (SCP Section 8.3.2.1.1.2)

Background and SCP Plans. This section described a suite of information to be gathered for design of the subsurface openings. The information required was primarily geared toward response of the host rock to the development and continued existence of the subsurface openings. Six different activities were listed and described.

Changes and Status. These data are currently being acquired in various ESF testing and monitoring programs. All data needs are still current with the exception of "borehole scale stress and deformation." The change from borehole emplacement to in-drift emplacement was first described in Section 4.1.17 of Progress Report #11 (DOE, 1995i). Because emplacement boreholes are no longer planned, the data needs associated with them are no longer needed.

Post-waste-emplacement environment (SCP Section 8.3.2.1.1.3)

Background and SCP Plans. This section discussed information needed to allow understanding of the conditions that will exist after heat-producing waste is placed in the repository. Six tasks were listed and described as required to understand the waste heat effects.

Changes and Status. All information described is still applicable and is being collected as part of the ESF single-heater and heated-drift tests. As discussed above for 8.3.2.1.1.2, information related to borehole emplacement is no longer needed.

Coupled interaction tests (SCP Section 8.3.2.1.2)

Background and SCP Plans. This section described the approach planned to address the coupled thermal, hydrologic, mechanical, chemical, and radiological phenomena that must be considered for design, construction, and performance analyses for the repository. The section included a table that summarizes 40 combinations of coupled processes to be investigated in given SCP studies or activities.

Changes and Status. The Project's general approach to investigating coupled site processes is consistent with that presented in this section. The Project is investigating the processes as described in Table 8.3.2.1-1, although some of the specific tests in the table have been canceled. Specifically, there has been no "well testing with conservative (8.3.1.2.3.1.6) or reactive (8.3.1.2.3.1.8) tracers throughout the site." The "heater experiment in unit TSw1" (8.3.1.15.1.6.1), "canister-scale heater experiment" (8.3.1.15.1.6.2), and "heated room experiment" (8.3.1.15.1.6.5) have not been conducted, but have been replaced by a single-heater test and drift-scale test in the ESF. These changes have occurred because the Project has pursued a more focused suite of tests than those described in the SCP. In addition, the single-heater and

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drift-scale tests are expected to accomplish most of the objectives of the tests described in the SCP in a more timely and cost-effective manner.

Design improvement activities and tests (SCP Section 8.3.2.1.3)

Background and SCP Plans. This section described the planned approach to optimizing design. The section stated that the Project was not seeking an optimum design solution, but instead was seeking a design that has been optimized to the point of providing an acceptable solution emphasizing certain characteristics. These characteristics included licenseability and simplicity. The section also provided a table of planned design tradeoff analyses.

Changes and Status. The approach taken to design optimization to date is consistent with the approach described in this section. The tradeoff analyses in Table 8.3.2.1-2 are part of the present program, although some of the results are not consistent with the titles of the tradeoff studies. For example, in-drift emplacement is now planned, and because of the change in emplacement mode and move to larger waste package designs waste packages are not planned to be transported by hoists. In addition to the tradeoff analyses shown in this table, the program has performed or will perform many other such analyses. In-drift emplacement was prompted by a design concept change to large-capacity waste packages. (The reasons for the shift to large, robust waste packages are discussed in the introduction, Section A.4 (waste package program) of this appendix.

Emplacing of waste packages in drifts instead of boreholes is expected to have significant advantages. Overall repository excavation costs are expected to be lower because boreholes are not necessary. Drift emplacement would allow the packages to radiate heat to a larger area and thus would help control maximum temperatures. Borehole emplacement of the larger waste package would result in violation of both the peak rock temperature goal (200°C) and the fuel cladding temperature goal (350°C). A severe seismic event with shear displacements in the repository horizon would be less likely to damage drift-emplaced waste containers than borehole-emplaced containers because drift emplacement provides extra clearance between the containers and the drift wall. Drift emplacement would simplify emplacement operations and would maintain flexibility of thermal loading because packages could be spaced as needed along the drift. Finally, boreholes appear to have a greater tendency to accumulate ground water and to confine the products of degradation. This tendency raises concerns about corrosion and criticality. Given that the borehole emplacement approach is no longer being considered, there are no activities associated with horizontal versus vertical emplacement borehole orientation nor with borehole spacing and length. Waste packages are to be transported via rail down the gently sloping (-2.15 percent) north ramp into the repository. Thus, there are no activities associated with hoisting of waste packages.

Repository modeling (SCP Section 8.3.2.1.4)

Background and SCP Plans. This section introduced the four following sections on various numerical modeling applications. Sections follow on geomechanical, seismic, ventilation, and safety analyses.

Changes and Status. This introductory material contains no specific information, so status is not relevant. The following discussions of Subsections 8.3.2.1.4.1 through 8.3.2.1.4.4 provide status on topics for this SCP section.

Geomechanical analyses (SCP Section 8.3.2.1.4.1)

Background and SCP Plans. This section described the understanding of geomechanical response current at the time the SCP was written. Listed were three types of analytical tools planned for providing perspectives on this response. The section then described the understanding of rock mass thermal response and three types of analytical tools planned for development to provide perspectives on this response. Next, the understanding of the combined contribution of excavation and thermal effects to rock mass response was described, and two methods planned for use in predicting thermomechanical response were mentioned. Types and scales of analyses planned to be considered were also discussed.

Changes and Status. Current understanding of the processes is consistent with that provided in the SCP. The analytical tools and analyses described are being used or are planned for use.

Seismic analyses (SCP Section 8.3.2.1.4.2)

Background and SCP Plans. This section listed five phenomena planned for consideration in seismic analyses.

Changes and Status. The Program is considering the phenomena described in this section in seismic analyses performed to date or planned.

Ventilation analyses (SCP Section 8.3.2.1.4.3)

Background and SCP Plans. This section provided a general description of the planned ventilation analyses and specifically stated that codes for ventilation analyses will be qualified for thermal effects. Two types of planned analyses were also discussed.

Changes and Status. The program is performing the types of ventilation analyses discussed in the section. The code being used for ventilation network analyses without thermal effects has been qualified. The original code used for ventilation analyses that include thermal effects was qualified, but recent updates to that code have not yet been qualified. The most recent code upgrade will be qualified before it is used for quality affecting work.

Safety analyses (SCP Section 8.3.2.1.4.4)

Background and SCP Plans. This section provided a brief statement that safety analyses would be conducted in addressing repository design criteria for radiological and nonradiological health and safety. The section stated that codes used for this purpose would be ones that have been proven through extensive past use in the nuclear industry.

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Changes and Status. The program is performing analyses consistent with those called for in this section. Codes used for this purpose are proven, nuclear industry codes.

Issue resolution strategy for Issue 1.11: Have the characteristics and configurations of the repository and repository engineered barriers been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.133 and (b) provide information for the resolution of the performance issues? (SCP Section 8.3.2.2)

Background and SCP Plans. This section presented the strategy planned to address 10 CFR 60.133 and to resolve performance issues. Figure 8.3.2.2-1a provided a detailed flowchart of this approach. The regulatory basis as described in this section included both 10 CFR 60.133 requirements and 10 CFR Part 960 guidelines (Subpart C sections 4-2-3 and 4-2-5). The section described four functions that the postclosure waste disposal system must satisfy: (1) select repository orientation, layout, etc., to contribute to containment and isolation; (2) limit water uses and chemical changes during construction; (3) limit excavation-induced changes in rock mass permeability; and (4) design thermal loading taking into account performance objectives and thermomechanical response of host rock. The section then identifies specific processes contributing to each function. Tables 8.3.2.2-1 through 8.3.2.2-4 provided specific performance measures, goals, and confidence levels for addressing these functions, and accompanying text amplifies the tables. Specific design basis statements were made, such as "The present design basis is that the underground excavations will be backfilled before repository closure."

Changes and Status. The current strategy for addressing this issue is generally consistent with the strategy presented in this section of the SCP. The four major functions described in the section are still valid and are being addressed in the current program. The types of performance measures described in the tables are generally being used in the current program. Those measures associated with borehole emplacement have been modified or deleted as appropriate to reflect the current emplacement concept. Because of the limited amount of blasting planned to be performed (none in the emplacement drifts), the performance measure for permeability change has been deleted. The confidence levels from the tables are being used to establish the need for additional testing and results. Many of the goals have changed as knowledge of the mountain has improved and as the emplacement mode has shifted from boreholes to horizontal in-drift. The major difference in the present design basis from that provided in the SCP section is that in-drift emplacement of waste packages has replaced borehole emplacement. Emplacement drift backfill is not currently part of the repository design basis. To date, performance assessment results indicate that although backfill could enhance repository ability to perform postclosure isolation functions, emplacement drift backfill is not needed to meet those performance objectives. All other excavations are planned to be backfilled before closure.

Information Need 1.11.1: Site characterization information needed for design (SCP Section 8.3.2.2.1)

Background and SCP Plans. This section described site characterization information believed at the time the SCP was written to be necessary to support design. The section

describes three products intended to satisfy the information need: (1) a data requirements list, (2) a reference thermal/mechanical stratigraphy, and (3) development of reference thermomechanical rock properties. The stratigraphy was to be based on a three-dimensional stratigraphy contained in an interactive graphics information system. Table 8.3.2.2-5 listed performance parameters, goals, needed versus current confidence, and expected values. The section also described the Interactive Graphics Information System, required for the usable area and flexibility evaluation, and listed data required for use in the Interactive Graphics Information System. In addition, products and approaches intended to be used to organize information to meet the information need were briefly discussed.

Changes and Status. The three major products described in this section are being developed by the program through the following documents:

- The data requirements list is contained in the Repository Design Data Needs report (CRWMS M&O, 1995c).
- The stratigraphy is being built using the Lynx geoscience modeling system and is described in two reports: Definition of the Potential Repository Block (CRWMS M&O, 1995d) and Definition of Repository Block Limits (CRWMS M&O, 1994b).
- Thermomechanical rock properties are contained in the Geographic Nodal Information Study and Evaluation System (GENISES), a data base containing site and engineering data, and in the Reference Information Base (DOE, 1995m).

The Interactive Graphics Information System is in place to support stratigraphy development. Thermomechanical rock properties are being entered in the Reference Information Base as called for in the section. The performance measures, goals, and needed confidence levels are included in the present program. The program is consistent with the products described in the section text. As discussed earlier, because waste emplacement in boreholes is no longer planned, the emplacement borehole-related information needs are no longer relevant.

Design Activity 1.11.1.1: Compile a comprehensive list of all the information required from site characterization to resolve this issue (SCP Section 8.3.2.2.1.1)

Background and SCP Plans. This design activity involved compiling in one place all information needed to resolve the issue, including applicable statistical requirements such as acceptable error and level of uncertainty.

Changes and Status. The Repository Design Data Needs report (CRWMS M&O, 1995c) summarizes the site data needed for surface and subsurface repository design. The report states what data are needed, when they are needed, and the degree of completeness to which they are needed for each design phase. The last aspect includes applicable statistical requirements consistent with the SCP. The three levels of completeness used in the report are substantially complete, bounded, and conservative. Data needs listed in SCP Table 8.3.2.2-5 were considered

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during the development of the report and those considered still valid (which includes most of the data needs) were incorporated into it.

Design Activity 1.11.1.2: Determine adequacy of existing site data (SCP Section 8.3.2.2.1.2)

Background and SCP Plans. This design activity involved determining adequacy of site data and determining where additional data are needed, using statistical methods. The results of these determinations would be used to recommend further data be acquired or trade-off studies be performed.

Changes and Status. The Repository Design Data Needs report (CRWMS M&O, 1995c) analyzes the adequacy of site data and using that analysis recommends additional data needs. The level of data completeness is estimated for each data need required for the various stages of repository design. The term "completeness" is used as a measure of the adequacy and sufficiency of data needed for the existing Program Plan schedule and scope. This is a subjective approach intended as a general planning guide. More quantitative ratings that measure data confidence by specifying statistical probabilistic limits have not been used because such a level of detail is more appropriate for the development of test programs. However, the following descriptors for completeness also consider data variability, which can be regarded as a qualitative measure of confidence:

- **Substantially Complete:** Data at this level are substantially complete and additional analysis or collection is not likely to significantly change the results or conclusions. Data variability (a combination of measurement uncertainty and inherent randomness), e.g., spatial distribution, is reasonably defined.
- **Bounded:** Realistic bounding values, with upper and lower extremes identified, have been established for data at this level. Data variability is moderately defined.
- **Conservative:** Data are sufficient to estimate credible extreme or worst case values, conditions, or assumptions. Data variability is approximately defined.

Design Activity 1.11.1.3: Document reference three-dimensional thermal/mechanical stratigraphy of Yucca Mountain (SCP Section 8.3.2.2.1.3)

Background and SCP Plans. This design activity stated that topical reports would be produced that will describe the three-dimensional stratigraphy of Yucca Mountain, relying on the Interactive Graphics Information System and recorded in the Reference Information Base.

Changes and Status. Work on this activity reflects the intent of the design activity. Work focuses on two areas: (1) definition of the thermal/mechanical units and (2) development of a three-dimensional computer model. Reports have been and are being developed as called for in the design activity, including Definition of the Potential Repository Block (CRWMS M&O, 1995d) and Definition of Repository Block Limits (CRWMS M&O, 1994b). The computer model LYNX is updated as new information is received. Data are being entered in the Reference

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Information Base (DOE, 1995m) as planned in the design activity to support development of a three-dimensional stratigraphy model. The model output, a three-dimensional profile of Yucca Mountain, is also planned to be entered in the Reference Information Base. Topical reports are not currently planned on this subject. Instead, this information will be contained in design analyses.

The LYNX modeling activity is integrated closely with the three-dimensional geologic framework and Integrated Site Modeling activity described in the discussion of SCP Section 8.3.1.4.2.3 in this Appendix. Relevant horizons and faults from the Integrated Site Modeling activity are used in the LYNX-based model to support design.

Though related, the two modeling activities have different content and purpose. The Integrated Site Modeling activity is constructed to be comprehensive to feed all hydrologic, properties, and transport models including performance assessment, while the design model provides geometric information in a focused geographic area. The Integrated Site Modeling activity covers 65 square miles, encompassing the entire conceptual controlled area boundary, while the design model is focused on the repository block. The Integrated Site Modeling activity contains 36 lithostratigraphic horizons from the surface to the top of the Paleozoic, while the design model extends only to the Calico Hills formation and uses a different grouping of the rock units.

Design Activity 1.11.1.4: Preparation of reference properties for the reference information base (SCP Section 8.3.2.2.1.4)

Background and SCP Plans. This design activity called for the development of topical reports that would give properties and describe how they were determined from field and laboratory measurements. The reports were to be compared with the issue requirements to ensure adequate data is available. Work to be performed in support of this design activity included rock characteristics, initial conditions of stress and temperature, geology (stratigraphy and structure), and design data.

Changes and Status. The Project has, through the 1996 draft revised Program Plan, systematically identified information needed to support licensing. The SCP Issue to which this design activity pertains is a part of the information base thought to be needed when the SCP was written. Now, in light of enhanced understanding of the site, the information currently expected to be needed is sometimes different from that described in the SCP. Therefore, the Project has not attempted to verify that the Reference Information Base contains all the information specified in the SCP. Instead, reliance is placed on completion of activities in the Program Plan to ensure the Reference Information Base contains sufficient information to support licensing.

Application of results (SCP Section 8.3.2.2.1.5)

Background and SCP Plans. This design activity reiterated the three products resulting from the information need described in SCP Section 8.3.2.2.1. This section stated that the required site data list would guide site characterization testing. The reference stratigraphy had

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been entered in the Reference Information Base to support design and performance analysis. The reference rock properties would also be incorporated in the Reference Information Base for the same purpose.

Changes and Status. The current program is using the information as called for in the SCP section. Documentation of information is as described previously.

Information Need 1.11.2: Characteristics of waste package needed for design of the underground facility (SCP Section 8.3.2.2.2)

Background and SCP Plans. This information need identified waste package information needed in the Reference Information Base to support design of the repository. The section described four specific waste package characteristics needed to resolve the issue (thermal decay, package size, package temperature constraints, and waste inventory). An integrated list of waste package input items was to be provided, and the completeness of the list would be checked by reviewing the processes and goals associated with the issue and by identifying interactions and predicted response of the site to the design. Three methods of determining waste package temperature information were described. Use of ORIGEN2 code or a like code was specified.

Changes and Status. Work is in progress to address all four waste package characteristics specified in this information need. Rather than compiling an integrated list of waste package input items, individual items are requested as needed and provided when available, typically by way of controlled documents. This informal approach improves responsiveness and integration between disciplines. The completeness of the design for the underground facility will in itself provide evidence that complete inputs have been provided. The current values being used in design are listed in the Controlled Design Assumptions Document. ORIGEN2 and other codes are being used as indicated in the information need. The rationale for the information need as stated in the SCP is still applicable. Some of the waste package characteristics are enumerated in the Engineered Barrier Design Requirements Document (DOE, 1995o) but quantified elsewhere. Information on thermal decay of commercial spent nuclear fuel and defense high-level waste is found in the LWR Radiological PC Data Base (CRWMS M&O, 1993b) and High Level Waste PC Data Base (CRWMS M&O, 1993c), respectively; information on size, temperature constraints, and waste inventory is found in the Controlled Design Assumptions Document (CRWMS M&O, 1996e). The documents listed as providing design information are obsolete. A more up-to-date description is given in the Mined Geologic Disposal System Advanced Conceptual Design Report (CRWMS M&O, 1996b). The specific information needed is generally still as listed in the SCP, but the following changes have occurred. Thermal power output is now considered to be a function of age, burnup, enrichment, and reactor type for commercial spent nuclear fuel. This information is contained in the LWR Radiological PC Database. Tolerances on the various quantities are not being addressed at present but may be addressed in the future. In current design efforts, waste package internal temperatures are emphasized more than surface temperatures because internal temperatures are considered more restrictive.

References are made in the SCP section to emplacement boreholes; for reasons described below in the discussion for 8.3.2.2.3.3, emplacement boreholes will not be used (CRWMS M&O, 1996b).

Design Activity 1.11.2.1: Compile waste package information needed for repository design (SCP Section 8.3.2.2.1)

Background and SCP Plans. This design activity involved determining what waste package information was needed for underground facility design, obtaining the data, and documenting it in the Repository Design Requirements Document.

Changes and Status. This design activity was addressed consistent with the intent of the SCP. Waste package information needed to support repository design was documented in the Controlled Design Assumptions Document. Current values are compiled and published in the Controlled Design Assumptions Document (CRWMS M&O, 1996e), LWR Radiological PC Data Base (CRWMS M&O, 1993b), and High Level Waste PC Data Base (CRWMS M&O, 1993c). Values are updated as necessary to reflect design changes. The information will be included in the appropriate design requirements documents after resolution of the document hierarchy, which includes elimination of the repository design requirements document. (See the discussion of Information Need 4.4.4 (SCP Section 8.3.2.5.4) in this appendix.

Application of results (SCP Section 8.3.2.2.2)

Background and SCP Plans. This section stated that waste package information resulting from addressing information need 1.11.2 would be used in designing the underground facility.

Changes and Status. The Project is meeting the intent of this SCP section. Waste package information is being used on an ongoing basis in support of repository design. As discussed previously, the borehole emplacement concept is no longer being pursued, and waste package information related to this concept is not required.

Information Need 1.11.3: Design concepts for orientation, geometry, layout, and depth of the underground facility that contribute to waste containment and isolation including flexibility to accommodate site-specific conditions (SCP Section 8.3.2.2.3)

Background and SCP Plans. This section described approaches planned to obtain data for determining orientation, geometry, layout, and depth of the repository. Table 8.3.2.2-6 listed five products planned to be used to satisfy the information need. Table 8.3.2.2-7 described information expected to be required to complete the five products with the required level of confidence. Finally, the section described how each product would be developed.

Changes and Status. The Project has addressed or is addressing all five products discussed in this SCP section. One significant difference, discussed further with respect to Design Activity 1.11.3.3, is that the Project is no longer considering borehole emplacement,

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because it is not feasible with the planned large waste packages currently for use. Also, although the change to in-drift emplacement was not the direct result of a performance evaluation, substantial waste package and repository performance benefits are expected to result from the change. All Table 8.3.2.2-7 input items are being obtained, with the exception that those related to borehole emplacement have been modified to apply to in-drift emplacement. The SCP descriptions of how each product will be developed are current except for the decision on vertical or horizontal borehole emplacement orientation, which is no longer irrelevant.

Design Activity 1.11.3.1: Area Needed determination (SCP Section 8.3.2.2.3.1)

Background and SCP Plans. This design activity was to determine the area required for the underground facility.

Changes and Status. This design activity is being addressed in a manner consistent with that described. Area expected to be needed does not differ substantially from that expected at the time the SCP was written, although the proposed layout has changed substantially because of changes in the emplacement concept and from other considerations. The emplacement area required has decreased somewhat because the planned repository thermal loading has increased; emplacement area required is inversely proportional to the thermal loading. Total area required includes thermal buffers, accesses, and underground support and operations areas (CRWMS M&O, 1996b).

Design Activity 1.11.3.2: Useable area and flexibility evaluation (SCP Section 8.3.2.2.3.2)

Background and SCP Plans. This design activity involved analyzing the structure and stratigraphy of Yucca Mountain to identify usable areas and to ensure adequate area was characterized, to produce drift layout arrangements, to ensure drift arrangements fit geology and structure, and to identify site geologic data requirements.

Changes and Status. This activity is proceeding as described. A three-dimensional computer model is being used to develop the boundaries of potential repository development (CRWMS M&O, 1995d). The boundaries being developed generally are in agreement with the primary area identified in the SCP (Mansure and Ortiz, 1984). Reconfiguration of the repository and use of a higher thermal load than planned in the SCP would allow all 70,000 MTU of waste to be placed west of the Ghost Dance fault. This would provide more flexibility in emplacement by allowing the potential usable area east of the Ghost Dance fault to be reserved for contingencies. The results of these activities, however, are not planned to appear in topical reports or be placed in the Reference Information Base as discussed in the SCP. Instead, these results will appear in design analyses, technical documents, and drawings.

Design Activity 1.11.3.3: Vertical and horizontal emplacement orientation decision (SCP Section 8.3.2.2.3.3)

Background and SCP Plans. This design activity was to provide the performance evaluation necessary to document the choice of vertical or horizontal emplacement.

Changes and Status. This design activity is not being addressed as described. The SCP contemplated placing relatively small waste packages in vertical or horizontal boreholes, which would then capped and sealed from the emplacement drifts. One waste package was planned for vertical boreholes, and multiple waste packages were planned for horizontal boreholes. The Project has subsequently substantially increased the size of waste packages for reasons discussed in the introduction to Section A.3 (Waste Package Program) of this appendix. The increased sizes placing them in boreholes impractical. The present emplacement scenario would have waste packages placed directly on pedestal supports in the center of emplacement drifts. The decision to not use borehole emplacement was not the direct result of a performance evaluation. Rather, it resulted from the change to large waste packages coincident with the multi-purpose canister concept. The Project decided to go to the multi-purpose canister concept on the basis of the cost efficiency and better long-term performance of producing and emplacing a smaller number of very robust, large capacity packages. Although the current Program approach does not emphasize multi-purpose canisters, significant performance advantages are expected to result from the planned in-drift emplacement of large, robust waste packages as compared with the borehole emplacement concept described in the SCP.

Design Activity 1.11.3.4: Drainage and moisture control plan (SCP Section 8.3.2.2.3.4)

Background and SCP Plans. This design activity provided postclosure design requirements for the layout of the underground facility that would result in limiting the amount of water in contact with waste packages to provide a favorable containment and isolation environment.

Changes and Status. This design activity is being addressed in a manner consistent with that described. Current design follows the SCP concepts. The repository on the whole would be sloped such that any water entering the repository would drain to a low point at the north end of the repository. The emplacement drifts would be sloped so water would drain from them to the access drifts. In addition, there would be a small “step” at the intersection of the emplacement drifts and the access drifts, that would make the invert of the emplacement drifts slightly higher than the invert of the access drifts. A high thermal load would keep temperature above boiling for an extended time period and thus would keep liquid-phase water from contacting the waste packages.

Design Activity 1.11.3.5: Criteria for contingency plan (SCP Section 8.3.2.2.3.5)

Background and SCP Plans. This design activity provided criteria for a contingency plan to address postclosure performance issues, such as fault standoff and thermal load adjustments.

Changes and Status. This design activity is being addressed in a manner consistent with that described. Flexibility is available to adjust for different thermal loads, to deal with unexpected loss of emplacement area, and to adapt to changed conditions. The current repository design (reconfigured from that shown in the SCP) and the planned use of a higher thermal load than in the SCP would allow all 70,000 MTU of waste to be placed west of the Ghost Dance

fault (upper emplacement block). This concept would provide more flexibility in emplacement by allowing the potential usable area east of the Ghost Dance fault (lower emplacement block), which is approximately 20 percent of the upper emplacement block area, to be reserved for contingencies. In addition, area north of Drill Hole Wash is being investigated for possible inclusion into the upper repository block.

Application of results (SCP Section 8.3.2.2.3.6)

Background and SCP Plans. This activity committed to using data from the resolution of information need 1.11.2 to support repository design.

Changes and Status. This activity is being addressed in a manner consistent with that provided in the SCP section.

Information Need 1.11.4: Design constraints to limit water usage and potential chemical changes (SCP Section 8.3.2.2.4)

Background and SCP Plans. This information need described methods and approaches for developing design constraints to limit water usage and potential chemical changes in the underground facility. Two products were identified as needed to address the information need: material inventory criteria and water usage criteria. Table 8.3.2.2-9 provided a list of parameters and information items needed to develop the products. The section also stated that two sets of criteria were necessary; the first was with regard to modification of the postclosure geochemical environment of the waste package as a result of preclosure activities, and the second was the degree of saturation of the host rock as a result of preclosure activities. Finally, some details were provided on how the material inventory criteria and water management criteria were to be developed.

Changes and Status. The program has developed material inventory criteria and water management criteria for the ESF. A similar process will be used to develop such criteria for the repository. The parameters and information called for in Table 8.3.2.2-9 are being addressed. The current approach is generally consistent with the discussion provided in the section for obtaining the products. The exceptions are that drilling of emplacement boreholes and types of materials in emplacement boreholes do not apply because of a change in the emplacement concept, and the current thermal loading is expected to keep the waste packages dry for a period significantly greater than 300 years.

Design Activity 1.11.4.1: Chemical changes resulting from the use of construction materials (SCP Section 8.3.2.2.4.1)

Background and SCP Plans. This design activity involved quantifying chemical changes such as changes in pH that result from using a given quantity of construction materials, using the approach described in the information need.

Changes and Status. Chemical changes as a result of introduction of construction materials have been quantified using the approach described in the information need. The potential long-term effects of using cementitious materials (concrete and grout), organic compounds and additives, and steel members are being studied. Methods of altering the pH of Portland™ cement are also being studied.

Design Activity 1.11.4.2: Material inventory criteria (SCP Section 8.3.2.2.4.2)

Background and SCP Plans. This design activity involved establishing limits on the inventory of materials that will be used in construction and operation of the underground facility and limits on the amounts of such materials to be left in the postclosure repository. The design activity called for using the approach discussed in the information need in this effort.

Changes and Status. The program is addressing this design activity in a manner consistent with the approach described in the information need. All tracers, fluids, and materials being used underground in the ESF must first be approved by the DOE. Limits on inventories of various construction materials are applied, as stated in the design activity. Criteria have been written specifically for materials used in the ESF, and these are expected to apply to the repository as well. Specific criteria for the repository will be developed as a result of performance assessment and design studies currently under way.

Design Activity 1.11.4.3: Water management criteria (SCP Section 8.3.2.2.4.3)

Background and SCP Plans. This design activity established limits on the amount of water to be used for underground facility construction and operation, indicating amounts and locations for individual operations and using the approach and obtaining the data described in the information need.

Changes and Status. The problem of water management criteria for repository construction has not been addressed because repository design is not sufficiently mature. On the basis of the current advanced conceptual design, however, some changes in emphasis to section 8.3.2.2.4 relative to water management criteria are expected. The SCP identified the use of water for drilling of emplacement boreholes as a primary concern. The current design for in-drift emplacement eliminates this specific issue. Nevertheless, the use of water for construction of repository access and emplacement drifts will need to be evaluated to establish the effects of added water on potential repository performance. Appropriate limits on water use based on this evaluation will be required so that any adverse effects of added water on potential repository performance are controlled to an acceptable level. Similar work providing criteria for the control of water use during site characterization construction and testing activities has been ongoing since FY 1992. This work, reported in Section 6.21 of the progress report, does not have an SCP reference (although it is responsive to NRC concerns in the Site Characterization Analysis (NRC, 1989) regarding site impacts during site characterization).

Application of results (SCP Section 8.3.2.2.4.4)

Background and SCP Plans. This section stated that information obtained for information need 1.11.3 would be used as input to advanced conceptual design and license application design reports and in the reference postclosure design. The section stated that the results of this information need would be (a) criteria placed on the preclosure design process and (b) inputs to performance assessment.

Changes and Status. Information obtained for this information need has been used as input to advanced conceptual design. It also will be used in the future as input to license application design, but not to a license application design report as planned in the SCP. There will not be a license application design report because the information that it would contain will be an integral part of the license application documentation. This information is also being used in performance assessment as appropriate.

Information Need 1.11.5: Design constraints to limit excavation-induced changes in rock mass permeability (SCP Section 8.3.2.2.5)

Background and SCP Plans. This information need provided approaches planned to be used to develop design constraints to limit changes in the rock mass permeability. Processes for limiting magnitude and extent of blast-induced permeability, limiting potential for subsidence by limiting extraction ratio and drift sizes, and backfilling drifts at decommissioning were identified along with their associated performance measures and tentative goals. The information need was planned to be satisfied through completion of two products: excavation methods criteria and a long-term subsidence control strategy. The section also provided the technical basis for addressing the information need and the parameters and input items expected to be obtained. Data and other information needed to satisfy the issue were cited in Table 8.3.2.2-11. Appropriate criteria were to be developed for guiding the repository design using information from waste package characteristics and ground-water travel time. The two products that were to be developed to satisfy this issue are described here in some detail: (1) Product 1.11.5-1 - Excavation Methods Criteria discussed the expectation that drifts would be constructed using drill and blast methods, including issues of worker safety and health and currently available technology; and (2) Product 1.11.5-2 - Long-Term Subsidence Control Strategy discussed the need for usability of access to the repository throughout the operational period, which requires prevention of subsidence during this period. Also discussed is the need to ensure that significant postclosure surface subsidence does not lead to the creation of preferred pathways for water migration. The section also discussed the expectation that drift and pillar stability analyses would be performed to estimate the extent and magnitude of loosening of the rockmass above a backfilled drift are stated.

Changes and Status. The program is, in general, addressing this information need as discussed in the SCP section. Excavation methods for the entire repository, with particular emphasis on the emplacement drifts, are being evaluated. The initial studies on excavation method have been documented in reports. The excavation system will be further analyzed during FY 1997, and preliminary drawings will be prepared. Preliminary requirements have been

developed, and equipment and excavation sequence and concepts have been evaluated with the particular goal of reducing excavation-induced changes in rock mass permeability. The current analyses differ from the SCP material in Table 8.3.2.2-10 and Product 1.11.5-1 in that all blasting has been eliminated in the emplacement area and from virtually all nonemplacement areas by using tunnel boring machines and roadheader type mechanical excavation equipment. Mechanical excavation should lead to less impact on the rock mass permeability by eliminating blast damage potential. Current plans differ from the excavation criteria in Table 8.3.2.2-11 because the current horizontal in-drift emplacement mode is different from the borehole emplacement, and, therefore, no work is being performed on borehole design. Long-term subsidence control strategy is being addressed as planned in SCP product 1.11.5-2 listed in Tables 8.3.2.2-10 and -11. Drift and pillar stability analyses are being performed using the best available data and appropriate thermal load range. Efforts are being made to minimize the drift sizes while meeting the operational criteria. The extraction ratio is being maintained within the limit used in the SCP-Conceptual Design Report (SNL, 1987) for vertical borehole emplacement. The analyses are being performed to evaluate the preclosure access requirement mentioned for this product, as well as to gauge the extent of disturbance by determining the long-term rock mass displacement.

A very preliminary evaluation was performed to evaluate the long-term subsidence potential. The difference from the parameters and input items listed in Table 8.3.2.2-11 is that backfilling of the emplacement drifts is currently being considered as an option to be maintained instead of being considered mandatory. Drift and pillar stability analyses are being performed without the backfill as a stabilizing factor. The design is being developed using the logic of developing requirements and criteria and performing conceptual and preliminary design to meet the preliminary requirements and develop new requirements. The process is similar to the one discussed in the SCP section.

Design Activity 1.11.5.1: Excavation methods criteria (SCP Section 8.3.2.2.5.1)

Background and SCP Plans. This design activity identified constraints to be placed on excavation methods because of postclosure performance considerations, using the approach identified in the information need. Table 8.3.2.2-11 presented the excavation parameters and input required to satisfy this information need for this activity.

Changes and Status. The program is addressing this design activity in a manner generally consistent with that described in the information need. However, no work is being performed on borehole design (indicated in Table 8.3.2.2-11, under the column of "Parameters and input items") because of the change made from borehole to in-drift emplacement. Furthermore, the SCP-Conceptual Design Report assumed that most or all the repository would be excavated by drill-and-blast methods because mechanical methods had not yet been proved feasible in the welded tuffs. This assumption was a function of the repository layout at that time. The repository layout has since been revised so that less than one percent of the repository is now expected to be excavated by drill-and-blast. Almost all of the repository, including all emplacement drifts, will be excavated by mechanical means, approximately 90 percent of which will be by tunnel boring machine and the remainder by machines such as a roadheader. Using a

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tunnel boring machine is generally considered to produce the least possible disturbance to the surrounding rock mass (smallest possible extent of the damaged zone). Tunnel boring machine feasibility has been demonstrated by the excavation of over 6000 m in the ESF.

Design Activity 1.11.5.2: Long-term subsidence control strategy (SCP Section 8.3.2.2.5.2)

Background and SCP Plans. This design activity was intended to develop a position regarding the potential for postclosure subsidence (and its impact on containment and isolation) and to determine whether current goals are adequate to limit potential for subsidence. The design activity would be addressed using the approach described in the information need. Table 8.3.2.2-11 provide the parameters and input required to satisfy this information need.

Changes and Status. The program has addressed this design activity in a manner generally consistent with the approach described in the information need. Conceptual studies have been performed and preliminary analyses are being performed in the area of work described in the SCP as product 1.11.5-2. The potential for subsidence has been addressed as follows. The current repository layout consists of a series of long parallel emplacement drifts separated by long parallel pillars. The possibility of ground subsidence is essentially eliminated by requiring the pillars to be large enough that they would not fail under the estimated stress regime. Empirical evidence (Peng, 1992) indicates that pillars will not collapse and surface subsidence will not occur if the excavation extraction ratio in the emplacement areas is less than 0.50. The current design criteria requires the excavation extraction ratio to be less 0.30; the current layout has an excavation extraction ratio of about 0.22, which further increases overall stability. The difference between the current approach and the parameters and input listed in Table 8.3.2.2-11 is that the SCP-Conceptual Design Report assumed that all emplacement drifts would be backfilled within 500 mm of the crown. The current design does not use backfill as a basis for design, although it also does not preclude backfilling. The analyses for long-term stability are being performed without assuming backfill in the emplacement drifts. If added in the future, backfill would only decrease the potential for subsidence.

Application of results (SCP Section 8.3.2.2.5.3)

Background and SCP Plans. This activity stated that the products and information developed under information need 1.11.5 could be used as input to reference postclosure design and as criteria for design of the preclosure repository.

Changes and Status. Information obtained for this information need is being provided to preclosure and postclosure design as indicated in this SCP section. The conceptual design was used as input to the total system performance assessment, and the current preliminary design will provide input to the total system performance assessment to support the viability assessment. The products 1.11.5-1 and 1.11.5-2 being developed under this information need provide input to the preclosure repository design in the areas of drift and pillar sizes, drift configuration and orientation, and ground support needs.

Information Need 1.11.6: Repository thermal loading and predicted thermal and thermomechanical response of the host rock (SCP Section 8.3.2.2.6)

Background and SCP Plans. This information need presented the approach to obtaining design thermal loading, taking into account performance objectives and thermomechanical response of the host rock. The information need was intended to be satisfied through five products: allowable areal power density, borehole spacing strategy, sensitivity studies, strategy for containment enhancement, and reference calculations. The information need would be resolved through analyses and information items listed in Tables 8.3.2.2-13 and 8.3.2.2-14. The section discussed the approaches planned to support development of the products and described the three scales of analyses expected to be performed to resolve the information need: container-scale, drift-scale, and far-field.

Changes and Status. The Project generally is following the approach described in the SCP section to address the information need. The five products are being obtained, but with some changes. Product 1.11.6-1 - Areal Power Density, expresses repository thermal load in terms of areal power density which has units of kW/acre. Thermal load is currently being expressed in terms of MTHM acre because this quantity is fixed (i.e., not age dependent) for a given waste package. For a given fuel acceptance scenario, the MTHM acre has an equivalent initial kW/acre. The Project is considering basing the spacing of waste packages on an equivalent energy density to smooth temperature variations resulting from spacings using kW/acre or MTHM acre. Two waste packages having the same MTHM could have significantly different initial heat outputs (kW), and two waste packages having the same initial heat output could have significantly different total heat output. Equivalent energy density considers the total heat output from a waste package over some period of time, such as 1000 years, and then spaces the waste packages based on total heat output.

Product 1.11.6-2 - Borehole Spacing is not relevant because the emplacement concept has changed from boreholes to horizontal-in-drift. However, the equivalent of borehole spacing for in-drift emplacement is waste package and drift spacing, which are being addressed.

Product 1.11.6-4 - Strategy for Containment Enhancement mentions the goal of keeping the waste packages dry by maintaining the temperature above boiling for 300 years. Under the current higher thermal loading being assumed by the project, most of the repository will be above boiling for substantially longer than 300 years.

Information items described in the tables in this section are being obtained except for thermomechanical properties of overburden. These data are not being obtained because there is little thermal effect in the overburden and, therefore, the data are not needed.

The three scales of analyses described in the information need are consistent with the approach to such analyses currently being pursued, except that the container-scale analyses do not consider borehole liners or the effects of borehole collapse. However, the equivalent of these, namely drift support systems and drift stability, are included in the drift-scale analyses.

Design Activity 1.11.6.1: Thermal loading for underground facility (SCP Section 8.3.2.2.6.1)

Background and SCP Plans. This design activity established allowable thermal loading as a function of waste age and burnup. The section stated that the effort should start with far-field calculations and should also consider near-field constraints. The approach was to be consistent with that presented in the information need.

Changes and Status. The approach to developing a design thermal loading is generally consistent with the approach described in the information need, except for a change of units (see previous discussion for the information need). Thermal loading in the SCP was expressed as the areal power density in units of kW/acre. Currently, thermal loading is expressed in MTHM/acre, which for a given fuel acceptance scenario corresponds to an average kW/acre. Current design is considering thermal loads of 80 to 100 MTHM/acre, which is higher than the thermal load associated with the SCP repository layout. The change from borehole to in-drift waste package emplacement required several thermal constraints to be modified or deleted. More emphasis is currently being placed on postclosure performance than was evident in the SCP. For example, the SCP had a not-to-exceed borehole wall temperature goal of 275°C, which was deleted in the Controlled Design Assumptions Document (CRWMS M&O, 1996e) as recommended by the thermal goal reevaluation report (CRWMS M&O, 1993d) because of the decision to not use borehole emplacement. In addition, the SCP had a goal to keep the majority of the borehole walls above boiling for more than 300 years. This goal was changed in the thermal goal reevaluation report to a goal to maximize the time the waste package stays above boiling consistent with the thermal strategy. There was also a goal in the SCP that boreholes should not load containers beyond the limits imposed under Issue 1.10. This goal, which would set limits on the load that a waste package could experience, does not appear in current Program requirements documents because of the change from borehole emplacement. Current studies are evaluating limitations on thermal loads necessary to prevent violation of thermal goals (CRWMS M&O, 1996t).

Design Activity 1.11.6.2: Borehole spacing strategy (SCP Section 8.3.2.2.6.2)

Background and SCP Plans. This design activity was intended to establish strategy for choosing borehole spacings as a function of waste thermal output such that all near-field constraints will be satisfied. The activity was intended to be addressed using an approach consistent with that described in the information need.

Changes and Status. With the change from borehole to in-drift emplacement, the focus of this activity shifted to a waste package and emplacement drift spacing strategy. Otherwise, the goal of this activity remains the same: develop waste package spacings such that near-field thermal goals are not violated and postclosure performance objectives are achieved (CRWMS M&O, 1996b).

Design Activity 1.11.6.3: Sensitivity studies (SCP Section 8.3.2.2.6.3)

Background and SCP Plans. This design activity was intended to determine predicted repository thermal and thermomechanical response to variations in model input data. The information would be used to evaluate adequacy of data gathered and to ensure goals have been met with proper confidence. The approach intended was described in the information need.

Changes and Status. The goal of this activity remains unchanged. Recent work has dealt with determining the sensitivity of repository thermal and thermal/mechanical response to the various parameters, including thermal loading, waste package spacing, emplacement drift diameter, age of fuel before emplacement, and backfill in emplacement drifts.

Design Activity 1.11.6.4: Strategy for containment enhancement (SCP Section 8.3.2.2.6.4)

Background and SCP Plans. This design activity was intended to document how design of the underground facility has taken into account containment and keeping the containers dry for 300 years. The approach intended was described in the information need.

Changes and Status. The goal of this activity and the approach to addressing it remain unchanged. Ongoing studies in support of the currently planned high thermal loading are concentrating on the means of maintaining the temperature of as many waste packages as possible above boiling for as long as possible (considerably longer than the 300 years mentioned in the SCP). Studies have concluded that increasing the waste loading at the edges of the underground facility, as suggested in product 1.11.6-4, would have an insignificant effect on repository performance.

Design Activity 1.11.6.5: Reference calculations (SCP Section 8.3.2.2.6.5)

Background and SCP Plans. This design activity provided a consistent set of calculations with proper quality assurance of thermal and thermomechanical response of host rock that can be used to support performance assessment. The approach intended was described in the information need.

Changes and Status. The goal of this activity and the approach to addressing it remain unchanged. Current work under this activity is concentrating on thermal modeling of the TSw2 thermal/mechanical unit for combined excavation, thermal, and seismic loads.

Application of results (SCP Section 8.3.2.2.6.6)

Background and SCP Plans. This section stated that information obtained for this information need would be input to advanced conceptual design and license application design reports, documented in the reference postclosure design, and used as criteria for repository design.

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Changes and Status. Information obtained for this information need was provided to the design organization for advanced conceptual design. The information also will be used to support the license application design and be documented in the reference postclosure design. There will be no license application design report because the information it would contain will be an integral part of the license application documentation.

Information Need 1.11.7: Reference postclosure repository design (SCP Section 8.3.2.2.7)

Background and SCP Plans. This information need was to be satisfied by developing of two products: (1) a reference postclosure design that would help form the basis of performance assessment and (2) documentation in the advanced conceptual design and license application design reports of compliance of the postclosure design with 10 CFR 60.133. The information need listed five information items that must be documented as part of the reference postclosure design: (1) location, size, shape, and drainage pattern of underground openings, (2) anticipated postclosure state of openings, (3) location, function, and design of seals, (4) criteria for dismantling underground structures and facilities, and (5) documentation of surface monuments, if any.

Changes and Status. As part of ongoing design work, the Project is documenting the reference postclosure design that will be used in performance assessment. The design is being documented in reports, analyses, and drawings and identified in the configuration management system data base. There will be no license application design report used for documenting postclosure design because the information it would contain will be an integral part of the license application documentation. The five information items described in the information need are being addressed, except that the postclosure state of the openings now refers to the emplacement drifts instead of the emplacement boreholes. Also, current plans are to backfill emplacement drifts only if there is a demonstrated performance need and not just because access is no longer needed.

Design Activity 1.11.7.1: Reference postclosure repository design (SCP Section 8.3.2.2.7.1)

Background and SCP Plans. This design activity established what information would constitute the reference postclosure design and documented the information in the advanced conceptual design and license application design reports.

Changes and Status. The goal of this activity remains unchanged. A list of information needed for performance assessment has been prepared. The design was documented in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b) and will also be documented for license application design. However, as explained previously in the discussion of the information need, design will not be documented in a license application design report.

Design Activity 1.11.7.2: Documentation of compliance (SCP Section 8.3.2.2.7.2)

Background and SCP Plans. The objective of this design activity was to document the determination of whether the postclosure design complied with the design goals of this issue in the advanced conceptual design and license application design reports.

Changes and Status. The goal of this activity remains unchanged. Preliminary documentation of compliance has been prepared for the design to date, as discussed in the MGDS Advanced Conceptual Design Report. The determination of whether the postclosure design is expected to comply with the design goals for this issue will be documented for license application design. However, as explained previously in the discussion of the information need, compliance will not be documented in a license application design report.

Application of results (SCP Section 8.3.2.2.7.3)

Background and SCP Plans. This section stated that the reference design produced to satisfy this information need would be placed in the Reference Information Base (DOE, 1995m) for use as input to performance assessment.

Changes and Status. The reference design is being documented, but not in the Reference Information Base. Instead, the design is being documented in reports, analyses, and drawings. Information being documented as a result of these activities is being used to support assessments of repository and waste package performance as specified in this SCP section.

Schedule for configuration of underground facilities (SCP Section 8.3.2.2.8)

Background and SCP Plans. This section provided a schedule for addressing Design Activities 1.11.1.1 through and 1.11.7.2.

Changes and Status. The schedule for obtaining information for key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Project has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.2.2.-15 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The program plan supporting the 2001 submittal, which was issued in December 1994 (DOE, 1994a), contains a schedule for accomplishing major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised in the future as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

Issue resolution strategy for Issue 2.7: Have the characteristics and configurations of the repository been adequately established to (a) show compliance with the preclosure design criteria of 10 CFR 60.130 through 60.133 and (b) provide information for the resolution of the performance issues? (SCP Section 8.3.2.3)

Background and SCP Plans. This section stated that the issue is concerned with the features of the repository that relate to radiological safety. Figure 8.3.2.3-1 showed the relationship of this issue to other issues and to the site characterization program. The section described the proposed licensing strategy for resolving the issue, including a logic diagram. The section also identified functional requirements and discussed performance allocation. Table 8.3.2.3-2 listed subfunctions in support of the functional goals, along with processes, performance measures, tentative goals, and confidence levels needed for each subfunction. Table 8.3.2.3-3 listed various parameters required for resolution of the issue. The text describes the approach to testing to ensure all goals are met including verifying that the as low as reasonably achievable principle had been met. Finally, the section describes how the information needs to address the issue would be approached and how they related to each other.

Changes and Status. The issue resolution strategy for this issue being pursued by the Project is consistent with that presented in this section (including the licensing strategy section). Performance allocation is being addressed by the functional analysis process currently under way. The logic diagram in Figure 8.3.2.3-2a is consistent with the current Program. Subfunctions in Table 8.3.2.3-2 and parameters in Table 8.3.2.3-3 are being addressed in requirements documents and subsequently in design. Table 8.3.2.3-3 and the text referred to 30 CFR Chapter I, Subchapters D, E, and N. The source for the statement is 10 CFR 60.131(9). Since that part of 10 CFR Part 60 was written, 30 CFR Chapter I has been reorganized and Subchapters D and E were eliminated as headings. The parts of 30 CFR that were in Subchapters D and E are now parts 18-29, 31-33, and 35-36 of Subchapter B.

The current approach to testing is consistent with the approach discussed in the SCP section. The current approach to addressing the information needs is consistent with the approach described in this section, except that, as noted previously, the design configuration information and results will not be placed into, or obtained from, the Reference Information Base.

Environmental data specified in Table 8.3.2.3-3 is being collected as follows. The eight meteorological parameters (wind speed, wind direction, atmospheric stability, mixing layer depth, average ambient temperature, atmospheric moisture, precipitation, and barometric pressure) are being monitored two ways. Except for mixing layer depth, the parameters are being monitored locally (within about 20 km) using a nine-station network in the vicinity of Yucca Mountain. This activity is discussed further in Section A.1.9.2 of this appendix. All the parameters are included in the Scientific Investigation Implementation Package for Regional Meteorology (CRWMS M&O, 1995b), whose scope includes the 80-km radius of Yucca Mountain described in the SCP. To date, recreational use of water bodies has not been examined to date but may be considered as part of the development of the repository license application. The Project is monitoring surface water runoff but so far has not emphasized a goal for surface

water runoff to surface water bodies. This work is discussed further in Sections A.1.9.1, A.1.9.3, and A.1.9.4 of this appendix.

Information Need 2.7.1: Determination that the design criteria in 10 CFR 60.131 through 60.133 and any appropriate additional design objectives pertaining to radiological protection have been met (SCP Section 8.3.2.3.1)

Background and SCP Plans. This information need stated that three site parameters were required: (1) concentrations of naturally occurring radon and its daughters in repository airstreams, (2) use of shielding properties of host rock, and (3) quantification of transport of radioactive materials to workers and the public. A list of site data required was provided and the logic process for addressing the information need was described.

Changes and Status. The parameters and data listed in the information need are being obtained. The current logic process to meeting the information need is consistent with that discussed in the SCP section.

Design Activity 2.7.1.1: Design evaluation for compliance with radiological safety design criteria and performance goals (SCP Section 8.3.2.3.1.1)

Background and SCP Plans. This design activity evaluated the repository design against radiological safety design criteria and performance goals. Parameters to be used were those listed in the information need. The activity was intended to consist of a complete radiological safety design analysis and performance goal assessment of the reference repository design, operating plan, and supporting analyses at each phase of design.

Changes and Status. As stated in the previous discussion for the information need, the parameters listed therein are being addressed subject to changes noted in the discussion of the issue resolution strategy for Issue 2.7. A performance assessment and preliminary MGDS hazards analysis were performed for and documented in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b). Safety analyses and additional performance assessments will occur in conjunction with design work to support the viability assessment and the license application.

The SCP outlined a comprehensive design for radiological controls, many of which have only been considered conceptually for the repository. Specifically, these include (a) monitors and controls that limit the dispersion of radioactive contamination in and from the repository, (b) radiation alarms for airborne radiation, (c) alarms for explosion and fire detection, and (d) instrumentation and control systems for other safety-related repository features. These instrumentation requirements have been considered. No impediments are forecast for eventual design and implementation based upon currently expected repository conditions. Analyses to determine the radiological environmental conditions related to such designs are expected during FY 1997, from which detailed design may proceed during subsequent fiscal year efforts.

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Structures, systems, and components important to safety are currently being evaluated as part of the ongoing Q-List activity. Compilation of the revised list is expected at the end of FY 1997 to reflect major repository design changes. The as low as reasonably achievable principle is being implemented in the design process.

Additionally, the NRC drivers for radiation protection controls are undergoing changes that are expected to be reflected in changes to 10 CFR Part 60. The changes expected include revisions that effectively would alter the radiation design limits for both worker and public exposure rates during both Class I and Class II accidents and events. Any such changes that occur will potentially drive changes in the program as envisioned in the SCP.

Application of results (SCP Section 8.3.2.3.1.2)

Background and SCP Plans. This section stated that information for this information need would be used in preclosure design and technical feasibility studies to demonstrate compliance with radiological safety design criteria and performance goals.

Changes and Status. Information obtained for this information need is being used in a manner consistent with that specified in this SCP section.

Information Needs 2.7.2 and 2.7.3: (1) Determination that the design criteria in 10 CFR 60.131 through 60.133 and any appropriate additional design objectives pertaining to the design and protection of structures, systems, and components important to safety have been met, and (2) Determination that the design criteria in 10 CFR 60.131 through 60.133 and any appropriate additional design objectives pertaining to criticality control have been met (SCP Section 8.3.2.3.2)

Background and SCP Plans. This information need listed site parameters required to address the need and provided a basic logic for addressing it.

Changes and Status. The Project is addressing this information need in a manner consistent with this section. The site parameters listed in the information need are being addressed.

Application of results (SCP Section 8.3.2.3.2.1)

Background and SCP Plans. This section stated that information obtained for this information need would be used directly to demonstrate compliance with radiological safety design criteria and performance goals.

Changes and Status. The Project is addressing this information need in a manner consistent with this section of the SCP.

Schedule for repository design criteria for radiological design (SCP Section 8.3.2.3.3)

Background and SCP Plans. This section of the SCP provided a schedule for addressing Design Activity 2.7.1.1.

Changes and Status. The schedule for obtaining information for key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Project has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.2.3-4 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The program plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishing major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised in the future as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

Issue resolution strategy for Issue 4.2: Are the repository design and operating procedures developed to ensure nonradiological health and safety of workers adequately established for the resolution of the performance issues? (SCP Section 8.3.2.4)

Background and SCP Plans. This section stated that the issue is concerned with the features of the repository that relate to mining (nonradiological) worker safety. Designs and procedures for the repository were to address at least 12 factors listed in the section. The section also discussed major factors affecting worker safety and included certain assumptions regarding whether several potential events or accidents should be of concern. A five-step approach to resolving the issue was presented in the text and graphically depicted in Figure 8.3.2.4-1. The text also listed "system subelements" that do and do not require site data. Tables 8.3.2.4-1 through 8.3.2.4-9 provided specific functions, processes performed, performance measures, goals, and needed confidence for achieving the goals.

Changes and Status. The issue resolution strategy for this issue being pursued is consistent with that presented in this section and the logic diagram in Figure 8.3.2.4-1. The 12 factors listed in the section are being addressed. The system subelement for borehole emplacement has been deleted. The functions and performance measures in Tables 8.3.2.4-1 through 8.3.2.4-9 are being addressed, but some of the tentative goals have been modified or deleted to be consistent with the change in the basic repository emplacement concept and other design changes. These goals deal with limiting rock damage caused by blasting (little or no blasting will now occur), rockfall criteria (being addressed by a robust full-circle type lining), air cooling power (now incorporated by specifying other ventilation parameters), and duration of

drift stability (now about 150 years, including a retrieval operation period, instead of 100 years). The current approach to addressing the information needs is consistent with the approach described in this section.

Information Need 4.2.1: Site and performance assessment information needed for design (SCP Section 8.3.2.4.1)

Background and SCP Plans. This information need required that information needed to implement design and operating procedures be identified. The proposed two-part approach to doing this involved (1) addressing the issue of developing and documenting the procedures and (2) identifying information needed to implement those procedures. The section then discussed how each part would be addressed. Next, specific parameters for the information need were identified. Finally, the logic for obtaining the information was briefly discussed.

Changes and Status. The current program is using the two-part approach described in the information need, including the parameters and logic process that were planned.

Design activity to verify access and drift usability (SCP Section 8.3.2.4.1.1)

Background and SCP Plans. This design activity described seven demonstrations and tests planned in the ESF to demonstrate that design and operating procedures were adequate for repository design.

Changes and Status. This design activity is being carried out essentially as described. The only significant difference is that the emphasis in the SCP on blasting studies has not occurred because of repository redesign, which will result in less than one per cent of the repository being excavated by drill-and-blast. (See the previous discussion for Design 8.3.2.2.5.1)

Activity 1.11.5.1: Design activity to verify air quality and ventilation (SCP Section 8.3.2.4.1.2)

Background and SCP Plans. This design activity provided an approach to designing the repository ventilation system using four specific parameters.

Changes and Status. This design activity is being carried out as described in the SCP.

Application of results (SCP Section 8.3.2.4.1.3)

Background and SCP Plans. This section stated that information obtained for the associated information need would provide the data base required to assess the adequacy of design and operating procedures for worker nonradiological health and safety.

Changes and Status. The information being obtained is being used as described.

Schedule for non-radiological health and safety (Issue 4.2) (SCP Section 8.3.2.4.2)

Background and SCP Plans. This section of the SCP provided a schedule for addressing Design Activities 4.2.1.1 and 4.2.1.2.

Changes and Status. The schedule for obtaining information for key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Project has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.2.4-10 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The program plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishing major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

Issue resolution strategy for Issue 4.4: Are the technologies of repository construction, operation, closure, and decommissioning adequately established for the resolution of the performance issues? (SCP Section 8.3.2.5)

Background and SCP Plans. This section stated that the issue was concerned with determining whether the repository can be designed, constructed, operated, and closed using reasonably available and proven technology. A five-step approach to resolving the issue was presented in the text and graphically depicted in Figure 8.3.2.5-1. Tables 8.3.2.5-1 through 8.3.2.5-12 provided specific functions, processes performed, performance measures, goals, and needed confidence for achieving the goals for 12 system elements. Finally, the section provided a list of five criteria planned to support the assessment that the technology is reasonably available.

Changes and Status. The issue resolution strategy for this issue being pursued and the logic diagram in Figure 8.3.2.5-1 is consistent with the current Program. The SCP text states that system elements not requiring site-specific data are not discussed further in the SCP, but will be addressed in a repository design plan. There will be no repository design plan. Instead, these elements will be addressed in design analyses and system design description documents (see the following discussion below for Information Need 4.4.4). The performance measures and parameters in Tables 8.3.2.5-1 through 8.3.2.5-12 are being addressed as part of ongoing design and site characterization except for those in Tables 8.3.2.5-5 and 8.3.2.5-10 that deal with borehole emplacement, which is no longer part of the repository design. Some of the tentative goals and expected values have been modified or deleted to be consistent with the change in the

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basic repository emplacement concept and other design changes. These goals deal with limiting rock damage caused by blasting (little or no blasting will now occur), rockfall criteria (being addressed by a robust full-circle type lining), air cooling power (now incorporated by specifying other ventilation parameters), and duration of drift stability (now about 150 years, including a retrieval operation period, instead of 100 years). The five criteria planned in the SCP for use in supporting the assessment are consistent with the current program approach.

Information Need 4.4.1: Site and performance assessment information needed for design (SCP Section 8.3.2.5.1)

Background and SCP Plans. This information need summarized the site-related parameters identified as being required by the remaining information needs under Issue 4.4. The section provides four observations in support of the technical basis for the information need and refers to the parameters in Tables 8.3.2.5-1 through 8.3.2.5-12 for use in addressing the information need. The section then provides a justification for selecting these parameters.

Changes and Status. The four observations in the information need are still considered valid. Exceptions stated in the preceding discussion for Issue 4.4 to the parameters in Tables 8.3.2.5-1 through 8.3.2.5-12 apply. The current program is consistent with the logic presented in the information need.

Application of results (SCP Section 8.3.2.5.1.1)

Background and SCP Plans. This section stated that the information obtained to address the associated information need would be used to address Issue 4.4 by providing information needed in Information Needs 4.4.2 through 4.4.10 to update the Reference Information Base (DOE, 1995m) for use in license application design and to provide guidance for site data gathering.

Changes and Status. The information obtained for Information Needs 4.4.2 through 4.4.10 is being used as described, except that very little, if any, of the information obtained will be placed in the Reference Information Base. Instead, the information will be presented in design analyses and system design description documents.

Information Need 4.4.2: Characteristics and quantities of waste and waste packages needed for design (SCP Section 8.3.2.5.2)

Background and SCP Plans. This information need was to serve as interface between waste package design and repository design. It would be considered satisfied when waste package-repository interface requirements were finalized and passed on to design requirements documents. The section provided four waste-related parameters needed to support the information need and a nine-point logic process to support the selection of the parameters.

Changes and Status. The current approach is generally consistent with the parameters and logic process described in the information need. The exceptions are those items specifically

related to (a) borehole emplacement (a design concept not currently under consideration) (b) the period of retrievability (increased from 50 to 100 years); and (c) the waste quantities (will not appear in the generic requirements document). The generic requirements document has been deleted from the document hierarchy. (See the following discussion on Information Need 4.4.) The waste quantities will be stated in the Controlled Design Assumptions Document (CRWMS M&O, 1996e) and in individual system design description documents.

Application of results (SCP Section 8.3.2.5.2.1)

Background and SCP Plans. This section provided a cross reference for how information from the associated information need would be used in other issues and information needs.

Changes and Status. The current program approach uses the information obtained in this information need as specified in the SCP section.

Information Need 4.4.3: Plan for repository operations during construction, operation, closure, and decommissioning (SCP Section 8.3.2.5.3)

Background and SCP Plans. This information need was to produce a plan for repository operations. The section described how design information was to be used to develop the operations plan and listed parameters planned as input to the plan. Finally, the section provided a logic process for developing the plan.

Changes and Status. The approach to developing the operations plan currently being pursued is consistent with that described, including use of the specified parameters and logic process. The repository operations plan will not be further described in a repository design plan because there is no such plan; instead, the operations plan will be described in a concept of operations document.

Design Activity 4.4.3.1: Operations plan to accompany the advanced conceptual design (SCP Section 8.3.2.5.3.1)

Background and SCP Plans. This design activity was to produce an operations plan to accompany advanced conceptual design that focused mainly on waste handling operations, including retrieval.

Changes and Status. A concept of operations (operations plan) was included in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b). As planned by the SCP, this plan focused on waste handling operations, including retrieval.

Design Activity 4.4.3.2: Operations plan to accompany the license application design (SCP Section 8.3.2.5.3.2)

Background and SCP Plans. This design activity was to produce an operations plan to accompany the license application design. The plan would contain the results of design decisions made during advanced conceptual design and would contain operations only for the selected emplacement option. Sufficient detail would be included to support radiological and nonradiological safety analyses.

Changes and Status. The concept of operations for viability assessment is being developed. A preliminary version has been published (CRWMS M&O, 1996w). This work will lead to a concept of operations for license application. The Project currently plans to develop the concept of operations in a manner consistent with that described in the information need.

Application of results (SCP Section 8.3.2.5.3.3)

Background and SCP Plans. This section described how the operations plan would be used.

Changes and Status. The Project plans to use the operations plan in a manner consistent with that described.

Information Need 4.4.4: Repository design requirements for construction, operation, closure and decommissioning (SCP Section 8.3.2.5.4)

Background and SCP Plans. This information need would be satisfied by the publication and control of the repository design requirements for each phase of repository design. The information need called for clearly documenting and maintaining in the repository design requirements the controlled assumptions and baseline design configuration. Requirements planned to be considered in generation of the repository design requirements were listed and a graphic requirements document hierarchy was given in Figure 8.3.2.5-2. A logic process was described for meeting the information need, including a description of how changes to the repository design requirements would be made. Table 8.3.2.5-14 provided an organization of repository design requirements documents.

Changes and Status. The current approach to documenting design requirements, organizing the design requirements documents, and controlling changes to the documents has changed from the approach provided in the information need. This change is because (a) the NRC commented that the flow down and traceability of requirements were cumbersome and (b) the DOE determined that requirements were written at too low a level of detail. The current approach addresses these concerns. The work required by this information need will be accomplished, but the requirements will not appear in the documents envisioned in the SCP. The generic requirements document discussed in the SCP has been superseded. The current requirements document hierarchy consists of the CRWMS Requirements Document (DOE, 1995t) (highest level), followed by an MGDS Requirements Document (DOE, 1996c)

(next highest level), followed by two equal level documents, the Repository Design Requirements Document (DOE, 1994f) and the Engineered Barrier Design Requirements Document (DOE, 1995o). The revised requirements document hierarchy will involve revising the first two documents to provide requirements generally written at a higher level than they are now. Requirements from the Repository Design Requirements Document and the Engineered Barrier Design Requirements Document will be incorporated at a higher level in the MGDS Requirements Document, and the two lower-level documents will then be deleted. Below the OCRWM document hierarchy, system description documents, organized by systems, structures, and components, will be used to implement applicable requirements and criteria.

Design Activity 4.4.4.1: Repository design requirements for license application design (SCP Section 8.3.2.5.4.1)

Background and SCP Plans. This design activity developed the repository design requirements for use in license application design. The section described plans for updating the Repository Design Requirements Document (DOE, 1994f) before the initiation of license application design; the update would contain substantially more detail on waste handling operations, a single emplacement orientation, and the results of numerous design decisions made during advanced conceptual design.

Changes and Status. The update to the repository design requirements described in the design activity will be made in a manner generally consistent with that described. This update will actually occur in the MGDS Requirements Document (DOE, 1996c) and the system description documents mentioned in the discussion of Information Need 4.4.4, which will replace the Repository Design Requirements Document.

Application of results (SCP Section 8.3.2.5.4.2)

Background and SCP Plans. The section stated that the principal users of information obtained for the associated information need would be designers responsible for developing reference designs for the repository and its seals. The section also provided a cross-reference to issues and information needs that would use the information.

Changes and Status. The Repository Design Requirements Document was originally planned to answer the issues and information needs identified when the SCP was written. However, these issues and information needs will now be addressed by the system description documents mentioned in the discussion of Information Need 4.4.4.

Information Need 4.4.5: Reference preclosure repository design (SCP Section 8.3.2.5.5)

Background and SCP Plans. This information need was intended to result in development of a reference postclosure design. The section stated that the SCP-Conceptual Design Report (SNL, 1987) was the reference design when the SCP was written and described how the advanced conceptual design and license application design would build on this design. The section also discussed planned development of design reports, topical reports, tradeoff

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studies, etc. In the logic section, the information need listed 10 supporting activities requiring site data and 7 that do not require site data.

Changes and Status. The current approach to developing and documenting the reference postclosure design is consistent with that described in the information need, except that the design is not being documented in the Reference Information Base (DOE, 1995m). Instead, the design is being documented in various documents in the project baseline. The list of supporting activities mentioned in the SCP is being accomplished.

Application of results (SCP Section 8.3.2.5.5.1)

Background and SCP Plans. This section stated how the reference designs will be used and provided a cross reference to other information needs that would use the information.

Changes and Status. The current approach to developing and using the reference design is consistent with that provided in the SCP section.

Information Need 4.4.6: Development and demonstration of required equipment (SCP Section 8.3.2.5.6)

Background and SCP Plans. This information need was the focal point for the equipment development program. Four principal products were planned: a list of equipment, designs for unique equipment, the equipment itself, and demonstrations to establish capabilities of the equipment. The section described briefly how these products would be used. Specific site parameters needed were listed. The logic process listed a six-step approach to the development and demonstration of equipment. Six system-elements considered potential candidates for equipment demonstration were listed. Described were the development and demonstration of a prototype emplacement borehole boring machine and site data to support that demonstration.

Changes and Status. The four products in this information need are being developed, and they are being used as described in the information need. The site parameters listed are being addressed. The logic process provided in the information need is consistent with the current approach, with two exceptions. First, proof-of-principle tests for some potential types of emplacement equipment will be performed if determined necessary after the license application instead of before it. This change is not considered a problem because, with the change in emplacement concept, potential repository emplacement equipment is much simpler than equipment that would have been needed to support borehole emplacement. Proof-of-principle tests for some other equipment types and operations (e.g., bridge cranes and welding of waste packages) may occur before license application submittal. The second exception is that the development process and proof-of-principle tests will be documented in design analyses and the system description documents mentioned in the discussion of Information Need 4.4.4, instead of in a repository design plan and topical reports. The boring machine discussion no longer applies because the machine described is for excavating emplacement boreholes, which are not needed for horizontal-in-drift waste package emplacement. Accordingly, the tests planned to be conducted in the ESF for this equipment will not be performed. Similarly, different

emplacement and retrieval equipment is now being considered to support in-drift emplacement. For normal conditions, retrieval equipment is assumed to be the same as emplacement equipment. The Project has successfully demonstrated use of a tunnel boring machine in the ESF at Yucca Mountain. Use of a roadheader in the ESF has met with limited success in the welded tuff at the repository level. The Project intends to let potential commercial manufacturers demonstrate the probable success of larger, more powerful roadheaders.

Application of results (SCP Section 8.3.2.5.6.1)

Background and SCP Plans. This section described how the equipment designs and performance would be used, including a cross reference to other information needs and issues.

Changes and Status. The Project plans to use equipment design and performance information in a manner consistent with that provided in the SCP section but modified by the equipment changes mentioned in the discussion of Information Need 4.4.6.

Information Need 4.4.7: Design analyses, including those addressing impacts of surface conditions, rock characteristics, hydrology, and tectonic activity (SCP Section 8.3.2.5.7)

Background and SCP Plans. This information need was the principal place where rock mechanics analyses, hydrologic analyses, and ventilation calculations were discussed. Table 8.3.2.5-15 listed products and studies to support this information need. Also listed were site parameters needed to perform the required analyses. Underground system elements that require structural analyses were discussed in detail, including discussions of understandings of the phenomena. Table 8.3.2.5-16 listed planned analyses. The information need stated that sensitivity analyses would be performed and discussed codes planned for use in analyses.

Changes and Status. The products, studies, and analyses planned in the SCP to address this information need are generally being developed. There have been, however, some significant changes resulting from changing from borehole emplacement to in-drift emplacement, which means in-drift emplacement equipment will be developed instead of borehole emplacement equipment. For the same reason, there will be no studies of emplacement borehole stability, borehole hydrology, and borehole liner compatibility, but similar studies will be conducted for in-drift emplacement. Other changes include a Project policy establishing a longer period of retrievability. The goal for retrieval is that all waste should be retrievable for 100 years after the beginning of emplacement (DOE, 1994a). This change was made because the Project has pursued a more focused approach that will include fewer studies than previously planned. The longer retrievability period will allow a longer period of performance confirmation and therefore increased confidence that the more limited scope of site characterization has provided adequate understanding of predicted site and repository performance. There has also been a change in ground support and lining strategy. The current concept in emplacement drifts is to install one robust ground support/liner system that is suitable for all ground classifications. This approach was chosen to simplify ground support design and reduce costs. This system would be installed immediately behind the tunnel boring machine. In all other excavations, temporary ground support compatible with the ground classification would be installed immediately behind

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the tunnel boring machine and a permanent liner would be installed later. Also, results of reference calculations will not be placed in the Reference Information Base (DOE, 1995m) for reasons mentioned in the discussion for Information Need 4.4.5. Sensitivity analyses are being used in manner consistent with the discussion in the information need; however, they are being performed for in-drift emplacement rather than for borehole emplacement. The codes currently being used or planned for use are consistent with the discussion of codes in the information need.

Application of results (SCP Section 8.3.2.5.7.1)

Background and SCP Plans. This section described how the information obtained for the associated information need would be used, including a cross-reference to other analysis areas.

Changes and Status. The Project plans to use information and analyses described in the associated information need in a manner consistent with that provided in the SCP section, with the exception of changes described in the preceding discussion for Information Need 4.4.7.

Information Need 4.4.8: Identification of technologies for surface facility construction, operation, closure, and decommissioning (SCP Section 8.3.2.5.8)

Background and SCP Plans. This information need evaluated the effectiveness of site elements that affect design, construction, and operations of the repository facilities during the preclosure period. Four criteria would be used for this purpose. The section described the product of the information need and listed site parameters required to be addressed to support the information need. Finally, the logic process intended to be used was described; the discussion included then-current understandings of the important processes and phenomena affecting the information need.

Changes and Status. The Project is using the four evaluation criteria provided in the information need to address the information need. The identified site parameters are being addressed. The logic process described in the information need and the understandings contained in the discussion are current. However, results will be documented in design analyses and system description documents instead of in the repository design plan and in topical reports. Also, there will not be a separate license application design report because the information that it would contain will be an integral part of the license application documentation.

Application of results (SCP Section 8.3.2.5.8.1)

Background and SCP Plans. This section described how the information obtained for the associated information need would be used, including a cross reference to other analysis areas.

Changes and Status. The Project plans to use information and analyses described in the associated information need in a manner consistent with that provided in the SCP section.

Information Need 4.4.9: Identification of technologies for underground facility construction, operation, closure, and decommissioning (SCP Section 8.3.2.5.9)

Background and SCP Plans. This information need constituted the assessment that all aspects of the underground facility could be constructed, operated, closed, and decommissioned using reasonably available technology. The assessment was to be included in a summary chapter of the documents that define the reference postclosure repository designs. A list of parameters needed, organized by system elements, was provided. The information need also described the logic process for addressing the information need, organized by system element.

Changes and Status. The approach to addressing the information need is generally consistent with that described. The list of parameters and the understandings and plans in the logic process are also generally valid. As stated in the previous discussion on Information Need 4.4.6, equipment demonstrations will occur after the license application is developed, not before as planned in the SCP. There will be no equipment development for borehole emplacement, but there will be comparable work for in-drift emplacement. The SCP conclusion that no additional work is needed to develop a rock handling system is still valid, even though the excavation will no longer be predominantly by blasting. Rock handling methods for excavation by tunnel boring machine were adequately demonstrated in the ESF. Documentation of the results will be in design analyses and the system description documents mentioned in the discussion for Information Need 4.4.4 instead of in topical reports as planned in the SCP. Also, there will not be a separate license application design report because the information that it would contain will be an integral part of the license application documentation.

Application of results (SCP Section 8.3.2.5.9.1)

Background and SCP Plans. This section described how the information obtained for the associated information need would be used, including a cross reference to other analysis areas.

Changes and Status. The Project plans to use information and analyses described in the associated information need in a manner consistent with that provided in the SCP section.

Information Need 4.4.10: Determination that the seals for shafts, drifts, and boreholes can be placed with reasonably available technology (SCP Section 8.3.2.5.10)

Background and SCP Plans. This information need would determine if reasonably available technology was available for emplacing shaft, drift, and borehole seals. A series of evaluations was planned. Summaries of the results would be provided in major design reports, and topical reports would be developed. Parameters needed to satisfy the information need were listed, and the logic process for obtaining the information discussed.

Changes and Status. The approach currently being taken to addressing this information need is consistent with that described in the information need, including the parameters and the logic process described. The only difference is the results will be documented in design analyses

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and the system description documents mentioned in the previous discussion for Information Need 4.4.4 instead of in topical reports as planned in the SCP. Also, there will not be a separate license application design report because the information that it would contain will be an integral part of the license application documentation.

Application of Results (SCP Section 8.3.2.5.10.1)

Background and SCP Plans. This section described how the information obtained for the associated information need would be used.

Changes and Status. The Project plans to use information and analyses described in the associated information need in a manner consistent with that provided in the SCP section.

Schedule for preclosure design and technical feasibility (SCP Section 8.3.2.5.11)

Background and SCP Plans. This section of the SCP provided a schedule for addressing Information Needs 4.4.1 through 4.4.10. Table 8.3.2.5-18 described major events and provided planned completion dates.

Changes and Status. The schedule for obtaining information for key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Project has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.2.5-18 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The program plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishing major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

A.3 SEAL PROGRAM (SCP SECTION 8.3.3)

A.3.1 Introduction

When the SCP (DOE, 1988) was written, seals for boreholes, shafts, ramps, and emplacement drifts were considered to be of potentially great importance to repository performance. Accordingly, an entire SCP section (8.3.3) was devoted to seals.

The Project's current approach to investigating seal issues is generally consistent with the approach presented in the SCP. However, current understanding of site processes and performance indicates that seal performance is not as significant an issue for overall repository performance as was believed when the SCP was written. Two factors have contributed to the Project decision to deemphasize seals: (1) the increase in thermal loading since the SCP was written, which lessens the potential for water to enter the drifts, and (2) preliminary results from total system performance assessments, which indicated acceptable performance was possible without accounting for the benefits from seals. Therefore, seal design and issue investigation have received a relatively low priority to date.

For the advanced conceptual design, the Project summarized previous seal work and established a seal design consisting of shafts, ramps, and boreholes, as well as backfill of all underground openings except emplacement drifts.

The studies and analyses described in the SCP will generally be performed to more definitively determine the need for and appropriateness of seals in various repository applications. Plans for specific investigations are described in the material that follows.

A.3.2 Summary of Changes in Seal Program

This section discusses in order each section contained in Section 8.3.3 of the SCP—the section that outlined the seal program. First, appropriate background is provided and SCP plans are given. Then the changes that have occurred since the SCP was written are discussed and the current Project status outlined. In this discussion, references to sections, tables, and figures are to the SCP unless otherwise stated.

Seal program (SCP Section 8.3.3)

Background and SCP Plans. This section described the activities necessary to develop seal designs and demonstrate seal performance. A one-page discussion that described what was contained in following sections.

Changes and Status. A separate status on this introductory section is not needed.

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Overview of the seal program (SCP Section 8.3.3.1)

Background and SCP Plans. This section provided a general discussion of the seal program planned, including the planned timing for seal testing, development, and installation. The section described planned seal testing activities, and Figure 8.3.3.1-1 provided planned sequencing of seal activities.

Changes and Status. The presently planned approach to seal testing and installation is consistent with the approach described, including activity sequencing and planned testing. Testing during site characterization activities, however, is currently in abeyance until a better determination of the need for seals is made.

Seal environment (SCP Section 8.3.3.1.1)

Background and SCP Plans. This section described the aspects of the site environment important to seal performance. Listed was example information needed for design and evaluation of seals.

Changes and Status. The current understanding of the site environment as applicable to seal performance is consistent with that presented in this section. Plans list to obtain the information shown in the section as being needed.

Seal components (SCP Section 8.3.3.1.2)

Background and SCP Plans. This section contained a detailed discussion of seal components and described important properties for prospective seal materials. The section stated that cementitious and clay materials have a high probability of creating acceptable seals and discussed supportive test results.

Changes and Status. The current understanding of seal components is consistent with that described in the SCP section.

Seal designs (SCP Section 8.3.3.1.3)

Background and SCP Plans. This section cross referenced other SCP sections and the SCP-Conceptual Design Report (SNL, 1987) for seal designs current when the SCP was written. The section states that the advanced conceptual design and the license application design would be the next two phases in seal design. Planned studies and evaluations to support seal design are discussed.

Changes and Status. For the advanced conceptual design, the Project summarized previous seal work and established seal design to consist of seals in shafts, ramps, and boreholes, as well as backfill of all underground openings except emplacement drifts. The studies and analyses described in the SCP section will be performed in order to more definitively determine the need for and appropriateness of seals in various repository applications.

Seal modeling (SCP Section 8.3.3.1.4)

Background and SCP Plans. This section briefly described the planned use of models and codes to support performance evaluations of seals.

Changes and Status. The planned approach to modeling seal performance is consistent with that provided in the SCP section.

Issue resolution strategy for Issue 1.12: Have the characteristics and configurations of the shaft and borehole seals been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.134 and (b) provide information for the resolution of the performance issues? (SCP Section 8.3.3.2)

Background and SCP Plans. This section described how all seals for the repository would be addressed, provided the approach to resolving the issue, and demonstrated the approach graphically in Figure 8.3.3.2-1. Figure 8.3.3.2-2 showed the potential sealing subsystem, seal locations, and seal components. Table 8.3.3.2-1 showed functions, processes, material properties, performance measures, tentative design goals, and needed confidence. Table 8.3.3.2-2 described general design constraints to be passed to Issue 1.11. Table 8.3.3.2-3 described site parameters, goals, confidence, etc., to support resolution of Issue 1.12. Table 8.3.3.2-4 listed miscellaneous information needed to resolve Issue 1.12. Table 8.3.3.2-5 showed design basis performance goals for the sealing subsystem.

Changes and Status. The current approach to addressing the seal issue is consistent with that provided in this SCP section. The parameters to be addressed in the tables are being addressed. The tentative design goals listed are being reevaluated for compatibility with the latest repository configuration and operations concepts. The performance goals described in the SCP are not being addressed because of the relatively low priority placed on seal performance and the expectation that regulations pertinent to seals are likely to change. When the regulations are established and an approach for seal performance assessment is developed for use in total system performance assessment, appropriate goals will be developed for seal performance.

Information Need 1.12.1: Site, waste package, and underground facility information needed for design of seals and their emplacement methods (SCP Section 8.3.3.2.1)

Background and SCP Plans. This information need was intended to obtain site, waste package, and underground facility data needed for seal design. The section discussed the parameters listed in this discussion of Issue 1.1.2 (SCP Section 8.3.3.2) in some detail, including understandings current at the time the SCP was written. Finally, the logic process applicable to addressing the information need was described.

Changes and Status. The current approach to obtaining information to support seal design is consistent with that described, including parameters to be addressed and the logic process planned for use.

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Application of results (SCP Section 8.3.3.2.1.1)

Background and SCP Plans. This section stated how the data obtained for the associated information need would be used.

Changes and Status. The Project plans to use the information obtained for this information need as described in the SCP section.

Information Need 1.12.2: Materials and characteristics of seals for shafts, drifts, and boreholes (SCP Section 8.3.3.2.2)

Background and SCP Plans. This information need described how seal materials would be developed, described what general types of information would be needed, and stated that parameters needed were covered in the discussion of Issue 1.12 (SCP Section 8.3.3.2). Testing plans were described in the information need. Table 8.3.3.2-6 listed potentially important seal component properties and why information on them was needed. This investigation was intended to collect information to confirm the geochemistry of the ground waters and rock units at the repository horizon. This information would be used to confirm the predicted effects on seal materials, especially those associated with elevated temperatures, caused by the emplacement of waste in the repository. This information was needed to ensure that the design for seals was compatible with the geochemical conditions under ambient and elevated temperature conditions. Laboratory testing to determine material properties, establishing of hydraulic conductivity of various seals materials and consolidation testing of crushed tuff, and in situ testing to evaluate seals under realistic conditions would be conducted to address Information Need 1.12.2.

Changes and Status. The approach to determining seal materials characteristics is consistent with that provided in the information need, including information needed and plans for testing. The objective has not changed since the SCP was issued, but the data needed to resolve this information need have not yet been obtained. The initial effort to establish the technical basis for developing seal designs for the sealing program, using on preliminary site geohydrologic data, has been documented (Fernandez et al., 1987). The specific objectives of this comprehensive study were to develop performance goals, to assess the need for seals, to develop design requirements, and to recommend potential sealing materials for the sealing system. A second report (Fernandez et al., 1993) discussed the field testing program and technical rationale for consideration in adopting a sealing strategy for site characterization boreholes and underground access ways. The report also discussed objectives and plans for a seal testing program consistent with the results of the evaluation of design, performance assessment, and regulatory requirements. From these studies, any additional tests necessary to meet performance objectives will be determined. Numerous tests have been conducted to derive a degradation model for cementitious materials emplaced in a tuffaceous environment. Some of these tests included hydrothermal experiments on samples of high-silica concrete and grout, numerical analysis to simulate the products of the laboratory experiments, and analysis to determine volumetric changes accompanying the reaction of cements and UE-25 J#13 water. During FY 1997 systems engineering studies are planned to evaluate design, performance

assessment, and regulatory requirements (including State and Federal) for sealing boreholes, shafts, and ramps. Systems engineering studies will also evaluate specific requirements for an abandonment plan for the surface-based drilling program, summarize and report these requirements, and evaluate the need for additional laboratory seal material properties and performance tests and in situ seals tests. In addition, objectives and plans for a seal testing program will be developed consistent with the results of the evaluation of design, performance assessment, and regulatory requirements. From these studies, any additional tests necessary to meet performance objectives will be identified.

Study 1.12.2.1: Seal material properties development (SCP Section 8.3.3.2.2.1)

Background and SCP Plans. The SCP contained no discussion under this heading.

Changes and Status. Not applicable.

Activity 1.12.2.1.1: Detailed property determination of cementitious-based and earthen materials (SCP Section 8.3.3.2.2.1.1)

Background and SCP Plans. This activity was to initiate laboratory testing to determine material properties for seal components. General testing plans were described.

Changes and Status. This activity is contained in Study Plan 8.3.3.2.2.1, "Seal Materials Properties Development." That document is in agreement with the work expected as described in the SCP.

Activity 1.12.2.1.2: Hydraulic conductivity and consolidation testing of crushed tuff (SCP Section 8.3.3.2.2.1.2)

Background and SCP Plans. This activity established the hydraulic conductivity and consolidation behavior of crushed tuff to support development of criteria for shaft and drift backfill. General test plans were described.

Changes and Status. This activity is contained in Study Plan 8.3.3.2.2.1, "Seal Materials Properties Development." That document is in agreement with the work expected as described in the SCP.

Design Activity 1.12.2.2: A degradation model for cementitious materials emplaced in a tuffaceous environment (SCP Section 8.3.3.2.2.2)

Background and SCP Plans. This activity was to develop a degradation model to provide insight into how material properties of seal components, especially permeability and strength, could alter after being in contact with tuff. General test plans were described.

Changes and Status. Future work in this area will depend upon future systems studies to determine the needs and functions of seals.

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Study 1.12.2.3: In situ testing of seal components (SCP Section 8.3.3.2.2.3)

Background and SCP Plans. This study was to initiate in situ testing to evaluate seal component behavior. The process was presented for determining the need for in situ testing (the last two steps of which were incomplete when the SCP was written). The section referred to the discussion on Issue 1.12 (SCP Section 8.3.3.2) for properties needed and provided a discussion of site properties needed for addressing Issue 1.12. Discussed were the adequacy of data needed, emplacement concerns, and details of possible tests and studies.

Changes and Status. The contents of Study Plan 8.3.3.2.2.3, "In Situ Testing of Seal Components" are generally in agreement with the work expected as described in the information need. This work is currently unfunded, and future work scopes will depend upon future systems studies to determine the needs and functions of seals.

Application of results (SCP Section 8.3.3.2.2.4)

Background and SCP Plans. This section stated how information obtained for the associated information need would be used.

Changes and Status. The approach is consistent with the SCP section.

Information Need 1.12.3: Placement method for seals for shafts, drifts, and boreholes (SCP Section 8.3.3.2.3)

Background and SCP Plans. This information need would develop the placement method for seals for drifts, shafts, and boreholes. Listed are specific parameters of interest and the logic process expected to be needed to address the information need.

Changes and Status. The present approach is consistent with the approach presented in the information need, including parameters needed and the logic approach.

Application of results (SCP Section 8.3.3.2.3.1)

Background and SCP Plans. This SCP section stated how information obtained for the associated information need would be used.

Changes and Status. The approach is consistent with the SCP section.

Information Need 1.12.4: Reference design of seals for shafts, drifts, and boreholes (SCP Section 8.3.3.2.4)

Background and SCP Plans. This information need would provide the reference design for seals. Parameters needed are those described in Information Need 1.12.1. The information need also provided the logic process planned for the seal design effort.

Changes and Status. The current approach to seal design is consistent with the approach provided in the information need.

Design Activity 1.12.4.1: Development of the advanced conceptual design (ACD) for sealing (SCP Section 8.3.3.2.4.1)

Background and SCP Plans. This SCP section contains no text.

Changes and Status. Status is not required.

Design Subactivity 1.12.4.1.1: Define subsystem design requirements (SCP Section 8.3.3.2.4.1.1)

Background and SCP Plans. The objective of this subactivity was to develop design requirements for seal components. The activity included seven tasks planned to support this effort.

Changes and Status. To date, little design work has been funded and performed on repository seals. A preliminary seal design was presented in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b). That design was adapted from the one shown in the SCP-Conceptual Design Report (SNL, 1987) by considering changes made to the layout since then. Because advanced conceptual design is complete, all work under this design activity is now closed. Uncompleted work will be performed to support the viability assessment and later as part of license application design.

Design Subactivity 1.12.4.1.2: Perform trade-off studies to support advanced conceptual design development (SCP Section 8.3.3.2.4.1.2)

Background and SCP Plans. This subactivity provided technical justification for selection of seal design options. The section explained the intended focus of advanced conceptual design work in this area, including seven planned trade-off studies.

Changes and Status. Seal trade-off studies per se were not performed as part of advanced conceptual design because of their relatively low priority. Two factors have contributed to a Project decision to reduce emphasis and overall funding for seals-related work: (1) the increase in thermal loading since the SCP was written, which lessens the potential for water to enter the drifts, and (2) preliminary results from total system performance assessments that indicated acceptable performance was possible without accounting for the benefits from seals. Some aspects of the Engineered Barrier System Performance Requirements Systems Study (CRWMS M&O, 1996s) are also applicable to this issue. Because advanced conceptual design is complete, all work under this design activity is now closed. Additional trade-off studies will be performed as determined necessary to support the viability assessment and later as part of license application design.

Design Subactivity 1.12.4.1.3: Develop advanced conceptual design for seals (SCP Section 8.3.3.2.4.1.3)

Background and SCP Plans. This subactivity provided design details that could be used to support license application design and performance assessment activities. The section stated that the advanced conceptual design would summarize the results of trade-off studies and described some specific information to be included.

Changes and Status. The MGDS Advanced Conceptual Design Report presented the seal design, but it did not summarize all the information described in the subactivity because little or no design work has been done on seals since the SCP-Conceptual Design Report was written. The advanced conceptual design for seals was adapted from the design in the SCP-Conceptual Design Report by considering changes made to the repository layout since then. Because advanced conceptual design is complete, all work under this design activity is now closed. Additional seals design will be performed to support the viability assessment and later as part of license application design.

Design Activity 1.12.4.2: Development of the license application design for sealing (SCP Section 8.3.3.2.4.2)

Background and SCP Plans. This SCP section contained no technical text.

Changes and Status. No status is required.

Design Subactivity 1.12.4.2.1: Define subsystem design requirements (SCP Section 8.3.3.2.4.2.1)

Background and SCP Plans. This subactivity refined design requirements for sealing components to support license application design.

Changes and Status. Work not performed under seals advanced conceptual design will be performed as part of the viability assessment and later as part of license application design. The exact scope of future work will depend upon future systems studies to determine the needs and functions of seals. The systems studies are expected to encompass the work scope described in the SCP, and determine how seals relate to the selected repository thermal strategy. Exact timing of the studies will depend on available funding.

Design Subactivity 1.12.4.2.2: Perform trade-off studies to support license application design development (SCP Section 8.3.3.2.4.2.2)

Background and SCP Plans. This subactivity provided technical justification for the selection of final seal designs. Several planned trade-off studies were listed.

Changes and Status. Trade-off studies, as expected in the SCP, will be performed as part of the viability assessment and later as part of license application design.

**Design Subactivity 1.12.4.2.3: Develop license application design for seals
(SCP Section 8.3.3.2.4.2.3)**

Background and SCP Plans. This subactivity provided the license application design for seals. Described were four activities to support this task.

Changes and Status. Seal design will be developed as part of the viability assessment and later as part of license application design. The approach to be taken is expected to be consistent with that described in the subactivity.

Application of results (SCP Section 8.3.3.2.4.3)

Background and SCP Plans. This section described how information obtained to address the associated information need will be used.

Changes and Status. The Program plans to use seal information obtained to support this information need in a manner consistent with that provided in the SCP section.

Schedule for seal characteristics (Issue 1.12) (SCP Section 8.3.3.2.5)

Background and SCP Plans. This section of the SCP provided a schedule for addressing studies and design activities related to sealing. Table 8.3.3.2-10 described major events and provided planned completion dates.

Changes and Status. The schedule for obtaining information for key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Project has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.3.2-10 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The program plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishment of major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

A.4 WASTE PACKAGE PROGRAM (SCP SECTION 8.3.4)

A.4.1 Introduction

The Project's waste package design has changed substantially from the design concepts described in the SCP (DOE, 1988). Most changes to the design that have occurred have been caused by the change from a thin-wall, borehole-emplaced waste package to a thick-wall, in-drift-emplaced waste package. This change was driven in part by DOE goals for earlier waste acceptance. In addition, the robust waste packages currently planned are believed to have many performance and cost advantages over the packages envisioned in the SCP. Large, robust waste packages would allow fewer waste packages to be built and emplaced, would require a smaller total number of welds, would have thicker walls to attenuate radiation, and would have greater mechanical strength than would the containers envisioned in the SCP. The robust, multibarrier packages would provide significantly longer containment than would the original thin-wall concept.

Emplacing waste packages in drifts is also expected to have significant performance and cost advantages over borehole emplacement. Drift emplacement would allow the packages to radiate heat to a larger area and thus would help control maximum temperatures. A severe seismic event with shear displacements in the repository horizon would be less likely to damage drift-emplaced waste containers. Drift emplacement would simplify emplacement operations and would maintain flexibility of thermal loading because waste packages could be spaced as needed along the drift. Boreholes appear to have a greater tendency to accumulate ground water and to confine the products of degradation.

Although the waste package design concept has changed substantially, the approaches embodied in the issue resolution strategies described in the SCP have not changed significantly. A more detailed discussion of how and why the waste package and emplacement concepts have changed can be found in the discussion of 8.3.4 that follows.

The Project's approach to investigating the near-field environment is also generally consistent with the approach described in the SCP, but the studies and activities described in the SCP have been reorganized. Although the currently planned work scope is similar to that planned in the SCP, one study was split into two studies, and numerous activities under the various studies have been canceled and superseded by new studies. These changes were made during the progress of site characterization for several reasons. In some instances, the changes reflected improved understanding of what information is needed to support performance assessment. In other instances, changes were made for convenience in organizing the work. The near-field discussions in this section provide a cross reference between the SCP studies and activities and the current studies and activities.

The following sections explain how the Project plans to implement the SCP with regard to designing the waste package and obtaining an understanding of the near-field environment to support performance assessment and ensure the environment does not compromise the ability of the waste package to perform its design functions.

A.4.2 Summary of Changes in the Waste Package Program

This section discusses in order each section contained in Section 8.3.4 of the SCP—the section that outlined the waste package program. First, appropriate background is provided and SCP plans are given. Then the changes that have occurred since the SCP was written are discussed and the current Project status outlined. In this discussion, references to sections, tables, and figures are to the SCP unless otherwise stated.

Waste package program (SCP Section 8.3.4)

Background and SCP Plans. This section described the general strategy for waste package development and demonstration of postclosure compliance. The strategy was shown graphically in Figure 8.3.4-1.

Changes and Status. The strategy remains largely intact, and performance is still allocated to the waste package and other components of the engineered barrier segment. The following changes have occurred. The waste package program is now governed by the revised draft Program Plan (DOE, 1996a). Assumptions about water quality made in the SCP have been modified because of advances in understanding of the environment; the current assumptions are that introduced materials and thermal effects can result in large changes in near-field water chemistry (Wilder, 1996). Container materials have been chosen for use in the viability assessment design (CRWMS M&O, 1996h), but testing will continue on a variety of corrosion resistant and corrosion allowance metals, as well as alternative container materials. Performance is still allocated not only to the containment barriers but also to the waste form and "engineered environment." "Engineered environment" means the components of the engineered barrier segment other than the waste package. Performance allocation to spent nuclear fuel cladding is being considered.

Throughout this section and its subsections, there are references to small, thin-walled, single-barrier waste packages that will be emplaced in vertical boreholes. The current approach is to use large, thick-walled, multibarrier waste packages that will be emplaced in drifts (CRWMS M&O, 1996b). This change will not be repeated in the discussions of lower-level SCP sections that follow unless there are ramifications for other aspects of the discussion.

Using large, thick-walled, multibarrier waste packages emplaced in drifts has many advantages over the packages envisioned in the SCP. Large packages would have a smaller surface area to volume ratio, so more costly materials and/or thicker layers could be used in the containment barriers without as great an effect on overall repository cost. With large waste package capacities, the number of packages would be reduced, so there would be fewer closure welds to be made and inspected. Thick container walls would absorb radiation, making the packages easier to handle by reducing measures required for radiation protection and reducing the effects of radiolysis on the near-field environment. Thick walls would also provide greater mechanical strength in the event of a handling accident. Multiple barriers reflect the defense-in-depth concept and allow the designer to choose different and complementary materials that provide longer containment over a wide range of conditions.

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Emplacing waste packages in drifts is also expected to have significant advantages. Overall repository excavation costs are expected to be lower because boreholes are not necessary. Drift emplacement would allow the packages to radiate heat to a larger area, and thus would help control maximum temperatures. A severe seismic event with shear displacements in the repository horizon would be less likely to damage drift-emplaced waste containers than borehole-emplaced containers because drift emplacement provides extra clearance between the containers and the drift wall. Drift emplacement would simplify emplacement operations and would maintain flexibility of thermal loading, because packages could be spaced as needed along the drift. Finally there would be fewer concerns about corrosion and criticality. Compared with drifts, boreholes appear to have a greater tendency to accumulate ground water and to confine the products of degradation.

Overview (SCP Section 8.3.4.1)

Background and SCP Plans. This section described three issues related to waste package development. Relationships between design- and performance-related issues used in performance allocation were discussed and presented graphically in Figure 8.3.4.1-1.

Changes and Status. The issues described in the SCP section remain central to current efforts. In spite of design changes, current plans are to have minimal ventilation and no backfill in emplacement drifts under normal operating conditions, so the waste package environment would not depend strongly on whether the repository is operational or closed. This assumption is consistent with that presented in the SCP section. Interaction of Issues 1.10, 2.6, and 4.3 with other issues is still as described in Figure 8.3.4.1-1. Issue 1.10 is still the only waste package design issue that involves the acquisition of site characterization data.

Waste package environment (SCP Section 8.3.4.1.1)

Background and SCP Plans. This section described in general terms the environment into which the waste package would be placed and the expected effect of the waste package on that environment. The section summarized the understandings of the environment current at the time the SCP was written.

Changes and Status. When the SCP was written, limited collapse of boreholes around the waste packages was expected and thus limited stresses from rockfall, although an oxidizing environment was clearly expected. Emplacement drifts are now expected to collapse eventually, and substantial loading by rock impact is possible. Questions have been raised about the assumption that the vadose water will be similar to UE-25 J#13 water, but water from the repository horizon is still not available. Thermal goals are still in effect (CRWMS M&O, 1996e), but the goals have been modified to reflect changed designs. Attempts are being made to use heat to reduce the aggressiveness of the environment.

Waste package components (SCP Section 8.3.4.1.2)

Background and SCP Plans. This section described considerations of waste package designs and discussed in very general terms the waste expected to be emplaced.

Changes and Status. The waste packages envisioned by the authors of the SCP were smaller and generally simpler than those of current designs. The general thrust of waste package design has changed because of ongoing efforts to provide long containment at a reasonable cost. Major changes as a result of these efforts were the planned use of a thick-walled, more robust waste container, and larger waste packages that could accommodate more waste. Current designs also add a second containment barrier, a basket and basket guides in disposal containers for spent nuclear fuel, and a canister guide in disposal containers for waste glass. DOE-owned spent fuel has been added to the Project baseline, and a waste package that would contain both waste glass and DOE-owned spent fuel is being designed. Various additional components may be needed to accommodate DOE-owned spent fuel. Rod consolidation at the repository is no longer in the baseline (CRWMS M&O, 1996e). Aggressive conditions are now accommodated by using thick-walled, multibarrier containers that include a highly corrosion-resistant barrier. Alternative materials are also still under consideration. Also see the previous discussion of the waste package program (SCP Section 8.3.4).

Waste package designs (SCP Section 8.3.4.1.3)

Background and SCP Plans. This section briefly described the general approach planned to be taken in designing the waste package, including understandings current at the time the SCP was written and objectives for the design work. The section emphasized efforts in designing for mechanical loads and containment.

Changes and Status. Current work continues to address the concerns noted in the SCP section, but emphasis on thermal design, long-term criticality control, and shielding has been substantially increased. In the current design approach, requirements have been placed on the handling loads that the waste packages must sustain (CRWMS M&O, 1996e), but the packages are so strong that there is little effect on design. Requirements for containment by the waste package under accident conditions have been quantified (CRWMS M&O, 1996e). Current goals for containment are more stringent (CRWMS M&O, 1996e) than those described in the SCP, in that containment is to be provided for 1000 years. This change was made because of Program emphasis on very long containment.

Waste package modeling (SCP Section 8.3.4.1.4)

Background and SCP Plans. This section briefly described the planned approach to waste package modeling in support of design and performance assessment.

Changes and Status. Waste package modeling has changed to the extent required by changes in design; notably, analyses of borehole failure have been replaced by analyses of rockfall. (See the previous discussion of the waste package program (SCP Section 8.3.4).)

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Processes included in postclosure modeling are essentially unchanged from those described in the SCP. Some processes, such as radionuclide transport within the waste package, will be modeled at a higher (bounding) level of abstraction than was planned in the SCP because of the complexity of flow in a flooded, partially degraded waste package.

Issue resolution strategy for Issue 1.10: Have the characteristics and configurations of the waste packages been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.135 and (b) provide information to support resolution of the performance issues? (SCP Section 8.3.4.2)

Background and SCP Plans. This section provided the overall strategy for dealing with two aspects of waste package postclosure behavior. The first is related to waste package properties and interactions with the environment; the second is testing and analysis to support performance assessment. The section presented the proposed approach to addressing these issues, both in text and graphically in Figure 8.3.4.2-1. Figure 8.3.4.2-2 demonstrated the proposed approach to modeling. Table 8.3.4.2-1 presented model hierarchy and model inputs for the issue, including needed confidence. Table 8.3.4.2-2 presented performance measures, tentative goals, and needed confidence for addressing the issue. Table 8.3.4.2-3 presented performance parameters and goals for the issue. Table 8.3.4.2-4 provided a list of input parameters for characterization models for the issue. The section also discusses a design envelope for the waste package that included eight considerations. Design goals were discussed for each consideration. A list of limits to alteration of water chemistry was also provided.

Changes and Status. Although the general approach described in this section is still applicable, numerous details of its application have changed. The structure of the model hierarchy for Issue 1.10 is generally still valid, but "Borehole Stability" (Figure 8.3.4.2-2) has been replaced by "Drift Stability" because of changes in design emplacement mode. In addition, synergistic effects (such as galvanic protection of one containment barrier by another) are now thought to have substantial effects on performance, but these effects were not evident from the model hierarchy. Effects of waste package degradation on criticality control were also missing from the hierarchy. Model inputs for Issue 1.10 in Table 8.3.4.2-2 are largely unchanged. Changes in design have required substantial changes in performance measures, parameters, and goals. Design basis loads for rock fall in Table 8.3.4.2-2 have not yet been determined. Tectonic processes are of little importance for drift emplacement, and the separate goal in Table 8.3.4.2-2 for containers breached by tectonic processes is no longer in effect. Waste package materials have been selected for use in the viability assessment design (CRWMS M&O, 1996h). Requirements have been set for the mechanical strength of the waste package (CRWMS M&O, 1996e). Goals for loads on waste packages (shown in Table 8.3.4.2-3) are no longer in effect because drift emplacement provides little control over such loads.

No longer in effect is the goal that the vadose water should remain similar to that in the undisturbed environment because emplaced materials and thermal effects are thought to cause significant changes in water chemistry, regardless of the thermal load. The quantity of water that contacts the waste packages may be large for a few packages, contrary to the SCP assumption. The current list of input parameters for models of containment and release is still being

developed based on testing data. Constraints on drift stability are now driven mostly by retrievability considerations. Current waste package design constraints are more closely related to providing long containment to control release of radionuclides than the SCP predicted. This approach has been taken because, when waste forms are isolated from the atmospheric environment of an unsaturated repository for an extended period of time, fission product decay histories result in lower releases of radioactivity when the waste packages are eventually penetrated. (See the previous discussion of waste package environment (SCP Section 8.3.4.1.1.) Lateral inhomogeneity may occur at such a fine scale that separation of the site into regions as suggested in the SCP section may be impractical; for example, one waste package may have a large water flux while its neighbors have small fluxes. Percolation rate and flow paths are still thought to be vital to performance. Recent investigators have given a variety of percolation rates; quantitative predictions in the SCP for water flux are for an obsolete design; ground-water focusing (rather than diversion as discussed in the SCP) is postulated to occur because of the disturbance of the host rock during excavation. Design goals in the SCP section for water flux control are no longer in effect because of the difficulty of predicting and controlling fluxes over long times, but fluxes are expected to be small. SCP design goals for drainage of emplacement boreholes are no longer in effect because of changes in design emplacement mode. SCP design goals for rock-induced load on the waste package are no longer in effect because the emplacement mode has changed, but efforts are ongoing to specify design basis rock falls applicable to the in-drift mode currently under consideration. Design goals for thermal loading have been modified; the emphasis is now on using decay heat to keep containers dry as long as possible rather than for an arbitrary period of 300 years as specified in the SCP because of Project emphasis on very long containment. The SCP goal of characterizing the inventory of primary radionuclides to within ± 20 percent is no longer in effect because the goal is considered inappropriately stringent. Related goals of using decay heat to provide a benign environment and of controlling criticality will have a similar effect.

Selection criteria are being used in place of SCP design goals for container materials (CRWMS M&O, 1996h). Several candidate materials have been considered for each waste package component, and the performance of these materials has been compared. Use of selection criteria is expected to provide an equivalent design benefit as would be obtained through use of design goals. The design goal for uniform oxidation and corrosion of container materials is no longer in effect because it is not applicable to a multibarrier design that incorporates a corrosion-resistant barrier. The SCP design goal for fabrication is still in effect; corrosion tests will include welded samples. SCP design goals for handling that limit impact loads and scratch depth are considered excessively stringent for the current, thick-walled waste container design, so it may be appropriate to relax the limits on the distance of fall or depth of scratch that can be tolerated. SCP design goals for the borehole liner are no longer applicable because current designs do not include this component. Limits to alteration of water chemistry are no longer in effect. Current designs use a full concrete lining for emplacement drifts, which could easily produce changes in pH that exceed the prescribed limit. However, these changes are expected to promote long containment because high values of pH (to a point) tend to result in low corrosion rates for carbon steel.

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Information Need 1.10.1: Design information needed to comply with postclosure criteria from 10 CFR 60.135(a) for consideration of the interactions between the waste package and its environment (SCP Section 8.3.4.2.1)

Background and SCP Plans. This information need was intended to show that relevant environmental factors would be considered in waste package design. The section provided a list of parameters to be addressed and briefly stated the logic planned to be used.

Changes and Status. The current Program approach is consistent with that described in the information need, including the list of parameters and the logic. The list of factors from 10 CFR 60.135(a)(2) is incomplete, but the missing parameters may be addressed in the future.

Design Activity 1.10.1.1: Consideration of 10 CFR 60.135(a) factors (SCP Section 8.3.4.2.1.1)

Background and SCP Plans. This design activity was intended to explicitly show that the factors specified in 10 CFR 60.135(a) and listed as parameters in the associated information need would be considered in waste package design.

Changes and Status. The current Program approach was consistent with that described in the design activity.

Application of results (SCP Section 8.3.4.2.1.2)

Background and SCP Plans. This section stated that analysis results under the associated information need would be used to show explicitly that the factors enumerated in 10 CFR 60.135(a) were considered and that properties or interactions do not compromise repository performance, waste package functions, or the geologic setting.

Changes and Status. Information obtained to address the associated information need is being used in a manner consistent with that described in the SCP section.

Information Need 1.10.2: Reference waste package designs (SCP Section 8.3.4.2.2)

Background and SCP Plans. This information need provided an approach to developing reference waste package designs. Parameters are listed and the planned logic process briefly described.

Changes and Status. Because of changes in program direction and demands for higher performance, waste package designs have been modified from those referenced in this section of the SCP. (Chapter 5 of this progress report describes current designs.) All physical characteristics identified are still applicable. The number of waste packages as a function of time is available by waste stream analysis (CRWMS M&O, 1996e). Configurations of packages for viability assessment design are available, but only without tolerances. Maximum waste package weights for advanced conceptual designs are available; weights for design to support the 1998

viability assessment are under development. Mechanical and thermal properties of component materials are available in the literature. Both output characteristics identified in the SCP are still applicable. Techniques are available to calculate both the heat generation rate and ionizing radiation flux.

Application of Results (SCP Section 8.3.4.2.2.1)

Background and SCP Plans. This section stated how reference and alternative waste package design information would be used.

Changes and Status. The strategy for application of waste package design results is basically unchanged. But alternative waste package designs are no longer being carried as planned in the SCP because of increased confidence in the adequacy of current designs.

Information Need 1.10.3: Reference waste package emplacement configurations (SCP Section 8.3.4.2.3)

Background and SCP Plans. This information need described the reference waste package conceptual design and information needed for further design development. Specific parameters are listed and a general logic process is discussed.

Changes and Status. The logic of the current program approach is consistent with the approach presented in the information need. The emplacement configuration, however, has been changed to multibarrier waste packages emplaced in drifts. This change is discussed further in Section A.4.1 of this appendix. In addition, alternative designs are no longer being carried because of increased confidence in the adequacy of current designs. Although the reference thermal loading has changed (CRWMS M&O, 1996e), thermal loading is still an important consideration as predicted in the SCP. The changes in the emplacement configuration cause corresponding changes in the list of parameters. The various borehole parameters listed in the SCP are irrelevant because there are no boreholes in current designs. Significant parameters now include waste package spacing, emplacement drift layout and dimensions, and configuration of waste package support hardware, invert, and other components of the underground facilities. Because the project baseline has been extended to include waste forms other than commercial spent nuclear fuel and glass waste forms, information on emplacement configuration for waste package types must also be extended to include these waste forms.

Application of results (SCP Section 8.3.4.2.3.1)

Background and SCP Plans. This section stated how reference and alternative emplacement configuration design information would be used.

Changes and Status. The current program approach uses information obtained for this information need in a manner consistent with that described in this SCP section. However, alternative designs are no longer being carried as planned in the SCP because of increased confidence in the adequacy of current designs.

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Information Need 1.10.4: Postemplacement near-field environment (SCP Section 8.3.4.2.4)

Background and SCP Plans. This information need was intended to evaluate the attributes of the near-field environment and to establish the extent of physical and chemical interactions expected between the waste package materials and water present in or mobilized from the repository host rock. Parameters to be addressed are listed. The section also provided a planned logic, which included a list of attributes that affect water chemistry.

Changes and Status. This information need was intended to ensure that interactions with the emplacement environment do not compromise the function of the waste packages. Compositions and amounts of water that may contact the waste package are of critical importance in evaluations of waste package performance. The investigation collects and analyzes data and develops and exercises models to determine the amount and composition of the water that may contact the waste packages. This information will be used to evaluate design configurations as well as containment and controlled release performance issues.

Significant advances in collecting the information required for this information need have been made. The G-Tunnel test was completed at the Nevada Test Site to improve understanding of the thermal-hydrological process in an underground environment and to evaluate prototype instruments and test methodologies. Laboratory experiments have been conducted and continue using core and small block samples for the determination of thermohydrologic properties, mineral kinetics, rock-water interactions, and coupled processes. Numerical analyses of hydrothermal, thermomechanical, and thermochemical interactions in the near-field environment are ongoing. A survey of introduced material interactions and a preliminary assessment of microbial populations have been completed. The Near-Field and Altered Zone Environment Report (Revision 1, Volume II) (Wilder, 1996) documents the status and results obtained to date on this information need. Drift-scale testing in the ESF and the large block test will be initiated.

As the draft study plans pertaining to this information need were written and revised, the associated studies and activities were reorganized. Study 1.10.4.1 was split into two studies (itself and 8.3.4.2.4.6, Introduced Materials). During the study plan writing process, the work was redistributed among activities in the four original studies. The cross linkage was originally described in several revisions of the Site Design and Test Requirements Document (DOE, 1995p). However, study plan objectives are not included in the current revision of the Site Design and Test Requirements Document. Instead, the documentation of the cross linkage between original and current activities will be maintained in this appendix to the semiannual progress reports, as described in the following sections.

Study 1.10.4.1: Characterize Chemical and Mineralogical Changes in the Postemplacement Environment (SCP Section 8.3.4.2.4.1)

Background and SCP Plans. This study established the compositional features of water that might contact the waste packages by determining the effects of chemical reactions on the rock-water system. The study had seven activities.

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Changes and Status. Before writing the study plan, the study was divided into two studies (near-field geochemistry and introduced materials). The approach planned to be taken in the two studies developed from study 1.10.4.1 is consistent with the approach described in the Study 1.10.4.1 section of the SCP. When the near-field geochemistry study plan was drafted, the activities supporting the "new" Study 1.10.4.1 were organized differently than in the SCP. To avoid confusion between similarly numbered "old" and "new" activities, the "new" activities were renumbered with higher numbers. The cross linkage of the original activities to the current activities is described in the following sections. The status of the current activities is provided in Chapter 5 of this progress report.

Activity 1.10.4.1.1: Rock-water interactions at elevated temperatures (SCP Section 8.3.4.2.4.1.1)

Background and SCP Plans. This activity, which was intended to establish the identity and abundance of reaction products that form during hydrothermal interaction of tuff and reference ground water at elevated temperatures, was deleted by a change to the Site Design and Test Requirements Document (DOE, 1995p). The objectives of the activity were moved to new Activities 1.10.4.1.8, 1.10.4.1.9, and 1.10.4.1.11.

Changes and Status. The breadth of this activity, as captured in the current activities, has increased. Some regions of the repository are expected to become saturated for various lengths of time; this activity will consider these situations. Some experiments will be done at lower temperatures than the 90°C stated because of advances in experimental capabilities. Water chemistries modified from the representative vadose water will be considered; these modifications are caused by the heat and the mobilization of water. Additional techniques such as flow-through reactors will be used, in addition to the Dickson-type rocking autoclave experiments. Experiments will include crushed tuff as well as wafers, and solid reaction products will be considered in the experiments.

Activity 1.10.4.1.2: Effect of grout, concrete, and other repository materials on water composition (SCP Section 8.3.4.2.4.1.2)

Background and SCP Plans. This activity was intended to test rock-water interaction in the presence of repository materials.

Changes and Status. This activity is now reported under Activity 1.10.4.5.1 because of changes to the Site Characterization Program Baseline, Revision 8 (DOE, 1995g). The change was made because, as alternatives to the SCP waste package design were proposed, numerous alternative materials for design elements have been considered. Subsequent to this change, an additional study has been identified (1.10.4.5) to characterize the effects of man-made/introduced materials on chemical and mineralogical changes in the post-emplacement environment. The approach planned to be taken in Activity 1.10.4.5.1 to address the objectives of Activity 1.10.4.1.2 is consistent with the approach described for the Activity 1.10.4.1.2 in the SCP.

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Activity 1.10.4.1.3: Composition of vadose water from the waste package environment (SCP Section 8.3.4.2.4.1.3)

Background and SCP Plans. This activity was intended to characterize the composition of vadose water in the unsaturated, preemplacement waste package environment.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document. The objectives of the activity are met by Study 8.3.1.2.2.7. (See Section A.1.1.2 of this appendix.) The approach planned to be taken in Study 8.3.1.2.2.7 to address the objectives of Activity 1.10.4.1.3 is consistent with the approach described for Activity 1.10.4.1.3 in the SCP.

Activity 1.10.4.1.4: Dissolution of phases in the waste package environment (SCP Section 8.3.4.2.4.1.4)

Background and SCP Plans. This activity was intended to determine the dissolution kinetics of the phases present in the waste package environment

Changes and Status. The activity was deleted by a change to the Site Design and Test Requirements Document. The objectives of the activity were moved to new Activity 1.10.4.1.10. In addition to addressing all the work described in the original activity using an approach consistent with the SCP text, the current activity will consider two additional parameters, surface area and solution composition.

Activity 1.10.4.1.5: Effects of radiation on water chemistry (SCP Section 8.3.4.2.4.1.5)

Background and SCP Plans. This activity was intended to determine the composition of water in the presence of a radiation field under postemplacement conditions.

Changes and Status. The activity was deleted by a change to the Site Design and Test Requirements Document and its objectives were moved to new Activities 1.10.4.1.12 and 1.10.4.5.7. The approach planned to be taken in the current activities to address the objectives of Activity 1.10.4.1.5 is consistent with the approach described for Activity 1.10.4.1.5 in the SCP.

Activity 1.10.4.1.6: Effects of container and borehole liner corrosion products on water chemistry (SCP Section 8.3.4.2.4.1.6)

Background and SCP Plans. This activity was intended to determine the effect of corrosion products on the composition of water in the waste package environment.

Changes and Status. The activity is reported under Activity 1.10.4.5.2 because of changes to the Site Characterization Program Baseline, Revision 8. This change was made because, as alternatives to the SCP waste package design have been proposed, numerous alternative materials for design elements have been considered. Subsequent to this change, an additional study has been identified (1.10.4.5) to characterize the effects of man-made/introduced

materials on chemical and mineralogical changes in the post-emplacement environment. In addition to addressing the all the work described in the original activity using an approach consistent with the SCP text, the current activity will consider one additional parameter, initial water composition.

Activity 1.10.4.1.7: Numerical analysis and modeling of rock-water interaction (SCP Section 8.3.4.2.4.1.7)

Background and SCP Plans. This activity was intended to examine effects and processes in natural systems for time periods and chemical conditions not duplicated by laboratory studies.

Changes and Status. This activity is also reported under Activity 1.10.4.5.1 because the activity was divided between geochemistry and man-made material activities in Revision 8 of the Site Characterization Program Baseline. This activity was deleted by a change to the Site Design and Test Requirements Document, and its geochemistry objectives were moved to new Activities 1.10.4.1.13, 1.10.4.1.14, and 1.10.4.1.15. The Project plans to perform work described in the original activity in a manner consistent with the approach described in the SCP. Other codes have also been evaluated, and some are being used, in addition to EQ3/6, because of the advances in geochemical computation capabilities. Reaction progress (in both the minerals and the fluid) along flow pathways is now being calculated in addition to reaction progress at a given location; this has also been made possible by advancements in the state of the art.

Study 1.10.4.2: Hydrologic Properties of Waste Package Environment (SCP Section 8.3.4.2.4.2)

Background and SCP Plans. This study was to establish the hydrologic properties of the near-field repository rock and the effect of thermal perturbations on those properties. Fracture versus matrix flow and gas-phase versus liquid-phase flow are addressed. The section describes how flow and transport models will be used, as well as how boundary conditions for waste package performance assessment will be developed.

Changes and Status. This study had three activities in the SCP (Activities 1.10.4.2.1, 1.10.4.2.2 and 1.10.4.2.3). When the study plan was written and subsequently revised, the material was organized differently than in the SCP. To avoid confusion between similarly numbered "old" and "new" activities, the "new" activities were renumbered with higher numbers (1.10.4.2.4, 1.10.4.2.5 and 1.10.4.2.6). The cross linkage of the original activities to the current activities follows. The status of the current activities is provided in Chapter 5 of this progress report.

Activity 1.10.4.2.1: Single-phase fluid system properties (SCP Section 8.3.4.2.4.2.1)

Background and SCP Plans. This activity was intended to establish the single-fluid-phase hydrologic properties of fractured and unfractured tuff under both isothermal conditions and a thermal gradient.

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Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document, and its objectives were moved to new Activities 1.10.4.2.4 and 1.10.4.2.5. The approach planned to be taken in the current activities to address the objectives of Activity 1.10.4.2.1 is consistent with the approach described for Activity 1.10.4.2.1 in the SCP.

Activity 1.10.4.2.2: Two-phase fluid system properties (SCP Section 8.3.4.2.4.2.2)

Background and SCP Plans. This activity, which was intended to establish the two-phase hydrologic properties of fractured and unfractured tuff under both isothermal conditions and a thermal gradient.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document and its objectives were moved to new Activities 1.10.4.2.4 and 1.10.4.2.5. The approach planned to be taken in the current activities to address the objectives of Activity 1.10.4.2.2 is consistent with the approach described for Activity 1.10.4.2.2 in the SCP.

Activity 1.10.4.2.3: Numerical analysis of flow and transport in laboratory systems (SCP Section 8.3.4.2.4.2.3)

Background and SCP Plans. This activity was intended to use laboratory-scale tests for initial development and validation of the flow and transport in laboratory systems.

Changes and Status. The activity was deleted by a change to the Site Design and Test Requirements Document and its objectives were moved to new Activities 1.10.4.2.5 and 1.10.4.2.6. The approach planned to be taken in the current activities to address the objectives of Activity 1.10.4.2.3 is consistent with the approach described for Activity 1.10.4.2.3 in the SCP.

Study 1.10.4.3: Characterization of the Geomechanical Attributes of the Waste Package Environment (SCP Section 8.3.4.2.4.3)

Background and SCP Plans. This study establishes the mechanical attributes of the near-field host rock.

Changes and Status. The original study from the SCP had one activity, 1.10.4.3.1 - Waste Package Environment Stress Field Analysis. When the study plan was written, the material was organized differently than in the SCP. The SCP activity was subdivided into three activities: (1) Block Stability Analysis, (2) Borehole Damage Analysis, and (3) Geomechanical Properties Analysis (Activities 1.10.4.3.1, 1.10.4.3.2, and 1.10.4.3.3, respectively). The cross reference between the original SCP activity and the current activities follows. The status of the current activities is provided in Chapter 5 of this progress report.

Activity 1.10.4.3.1: Waste package environment stress field analysis (SCP Section 8.3.4.2.4.3.1)

Background and SCP Plans. This activity was intended to estimate the time-dependent stress field and displacements of the rock in the waste package environment. This section listed five parameters to be addressed and described what evaluations will be performed.

Changes and Status. The Project plans to use the three current activities created to reorganize this activity to address the information described in the original activity in a manner consistent with the SCP text.

Study 1.10.4.4: Engineered Barrier System Field Tests (SCP Section 8.3.4.2.4.4)

Background and SCP Plans. This study was to bring about the field tests needed to validate and establish the applicability of laboratory studies to the repository block. The section discusses use of prototype tests to develop test procedures and protocols.

Changes and Status. The original study from the SCP had three activities: 1.10.4.4.1 - Repository Horizon Near-Field Hydrologic Properties, 1.10.4.4.2 - Repository Horizon Rock-Water Interaction, and 1.10.4.4.3 - Numerical Analysis of Fluid Flow and Transport in the Repository Horizon Near-Field Environment. When the study plan was written and subsequently revised, the material was organized differently than in the SCP. The current activity organization is: 1.10.4.4.1 - In Situ Testing, 1.10.4.4.2 - Sampling and Sample Analyses, and 1.10.4.4.3 - Pre- and Post-Test Calculations. The cross linkage of the original activities to the current activities follows. The status of the current activities is provided in Chapter 5 of this progress report.

Activity 1.10.4.4.1: Repository horizon near-field hydrologic properties (retitled In Situ Testing) (SCP Section 8.3.4.2.4.4.1)

Background and SCP Plans. This activity was intended to determine the in situ hydrologic properties of rock in the repository horizon under thermally perturbed conditions. This section listed eight parameters to be addressed and also discussed how instrumentation would be deployed and stated that laboratory-scale hydrologic studies would be performed.

Changes and Status. The approach planned to be taken in the new activities to address the objectives of Activity 1.10.4.4.1 is consistent with the approach described for the activity in the SCP.

Activity 1.10.4.4.2: Repository horizon rock-water interaction (retitled Sampling and Sample Analysis) (SCP Section 8.3.4.2.4.4.2)

Background and SCP Plans. This activity was intended to determine the effect on water chemistry of thermal perturbation of the near-field environment. This section listed four parameters to be addressed and also described how instrumentation would be deployed and how

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tests would be performed. Finally, the section provided a listing of models and technical procedures planned to support the activity.

Changes and Status. The approach planned to be taken in the current activities to address the objectives of Activity 1.10.4.4.2 is consistent with the approach described for the activity in the SCP.

Activity 1.10.4.4.3: Numerical analysis of fluid flow and transport in the repository horizon near-field environment (retitled Pre- and Post-Test Calculations) (SCP Section 8.3.4.2.4.4.3)

Background and SCP Plans. This activity was intended to validate and calibrate fluid flow, temperature, and transport models using waste package-scale field studies. This section listed ten parameters to be addressed and also described in general terms the approach to be taken to addressing the activity, including studies to be performed and models planned to be used. The section also provided a list of technical procedures to be used to address the activity.

Changes and Status. Some changes from the SCP description of this activity have occurred. The last paragraph in the SCP description of this activity describes an in situ test to monitor the movement of sorbing and nonsorbing species; the activity includes numerical analysis of the test. Current plans for in situ tests do not include such a test before license application submittal. The use of tracers is not feasible in the drift-scale (heater) test because its instruments are primarily installed from boreholes drilled from the heated drift. Some tracer testing is being done as part of the large block test (in a surface outcrop of TSw2 tuff), but the lack of confining stress disqualifies these elements of the test from being "in situ." Therefore, transport aspects of the codes used in this activity will be benchmarked primarily to laboratory-scale testing, most of which was described in other parts of the SCP.

Study 1.10.4.5: Characterize the Effects of Introduced Materials on Water Chemistry in the Postemplacement Environment (new study added since the SCP)

Background. The objective of this study was to identify significant chemical modifications of the near-field environment from what would be expected under geological conditions. The modifications would be caused by the construction and operation of the repository and the postclosure conditions (e.g., radiation and thermal flux) as determined by repository design. In addition to construction materials, a complete picture of the modified chemical and hydrological system thus includes introduced air and water, the reintroduction of crushed tuff or muck rock (e.g., backfill), and the introduction of microbial populations.

Changes and Status. This study did not exist in the SCP. It was developed from aspects of the near-field geochemistry study (1.10.4.1) that included the effects of introduced materials and radiation from the waste packages. The original organization of the draft study plan included four activities. When the draft study plan was revised, the material was organized differently than in the first draft. To avoid confusion between similarly numbered activities in the initial draft (which was captured in the Site Design and Test Requirements Document) and the

subsequent draft, the current activities were renumbered with higher numbers. The cross linkage of the original activities to the current activities is described below. The status of the new activities is provided in Chapter 5 of this progress report.

Activity 1.10.4.5.1: Effect of grout, concrete, and other repository materials on water composition (new activity added since the SCP)

Background. The objective of the activity was to conduct solubility, stability and reactivity experiments to determine the effect of grout, concrete, and other repository materials on water composition.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document, and its objectives were moved to new Activities 1.10.4.5.5, 1.10.4.5.6, 1.10.4.5.7, 1.10.4.5.8, and 1.10.4.5.10.

Activity 1.10.4.5.2: Effects of container and borehole liner corrosion products on water chemistry (new activity added since the SCP)

Background. The objective of the activity was to conduct solubility, stability and reactivity experiments to determine the effect of container and borehole liner corrosion products on water chemistry.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document, and its objectives were moved to new Activities 1.10.4.5.6, 1.10.4.5.7, and 1.10.4.5.10.

Activity 1.10.4.5.3: Effects of introduced materials in presence of radiation field (new activity added since the SCP)

Background and SCP Plans. The objective of this activity was to conduct the interaction experiments described in Activities 1.10.4.5.1 and 1.10.4.5.2 in the presence of a radiation field to identify potential effects on the predicted natural chemical reactions.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document, and its objectives were moved to new Activity 1.10.4.5.7.

Activity 1.10.4.5.4: Numerical analysis and modeling of introduced materials/water interaction (new activity added since the SCP)

Background and SCP Plans. The objective of this activity was to develop the necessary codes and to conduct predictions and simulations of experiments and repository performance with respect to introduced materials effects on the near-field environment.

Changes and Status. This activity was deleted by a change to the Site Design and Test Requirements Document, and its objectives were moved to new Activity 1.10.4.5.11.

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Application of results (SCP Section 8.3.4.2.4.5)

Background and SCP Plans. This section describes which information needs and investigations would be addressed using information from the activities preceding this section.

Changes and Status. The Project plans to use the information in the manner described in this SCP section.

Schedule for postclosure waste package characteristics (SCP Section 8.3.4.2.5)

Background and SCP Plans. This section of the SCP provides a schedule for addressing information needs and studies for postclosure waste package characteristics.

Changes and Status. The schedule for obtaining information for many key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Program has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.4.2.-5 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The Program Plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishing major Program activities, though it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

Issue resolution strategy for Issue 2.6: Have the characteristics of the waste packages been adequately established to (a) show compliance with the preclosure design criteria of 10 CFR 60.135 and (b) provide information for the resolution of the performance issues? (SCP Section 8.3.4.3)

Background and SCP Plans. This section provided the approach to resolving the issue of compliance with preclosure design criteria of 10 CFR 60.135. Figure 8.3.4.3-1 provided a logic diagram of the process planned to address the issue. Table 8.3.4.3-1 listed the major preclosure functions or characteristics derived from the regulatory criteria for the waste packages.

Changes and Status. The general approach to resolving Issue 2.6 still follows the description in the SCP, but the following changes have occurred. Waste package requirements are documented in the Engineered Barrier Design Requirements Document (DOE, 1995o), which has a broader scope than the requirements document envisioned by the SCP in that it also includes requirements for components of the engineered barrier other than waste package.

Development of waste packages (shown in Figure 8.3.4.3-1a) is now governed by the Waste Package Development Technical Document (CRWMS M&O, 1996qq). There have also been several changes to the quantitative performance goals given in the SCP (Table 8.3.4.3-1). The goal for containment is now that 99 percent of waste packages should remain intact for 1000 years (CRWMS M&O, 1996e); the preclosure goal is that the probability of breach of an individual waste package should be less than 1×10^{-6} per year (CRWMS M&O, 1996e). Legibility of the waste package identifiers to the end of the period of retrievability is still a requirement (DOE, 1995o). Current waste package designs for commercial spent nuclear fuel will accommodate about 96 percent of such fuel; other approaches (such as different package designs, package derating, or aging) will be developed for other fuel. This approach provides coverage of all waste but limits costs for most waste packages. The goal for retrieval is that all waste should be retrievable for 100 years after the beginning of emplacement (DOE, 1995o). This change was made because the Project has pursued a more focused approach that will include fewer studies than previously planned. The longer retrievability period will allow a longer period of performance confirmation and therefore increased confidence that the more limited scope of site characterization has provided adequate understanding of predicted site and repository performance.

Information Need 2.6.1: Design information needed to comply with preclosure criteria from 10 CFR 60.135(b) for materials, handling, and identification of waste packages (SCP Section 8.3.4.3.1)

Background and SCP Plans. This information need provided the general approach to obtaining design information needed to comply with preclosure criteria from 10 CFR 60.135(b). The section listed and described four parameters to be addressed.

Changes and Status. The design criteria of 10 CFR 60.135(b)(1) through (4) concern the types of materials that may be used in a waste package, design for handling, and unique identification. These criteria are still in effect and are being considered. Commercial spent nuclear fuel and high-level waste glass are in compliance with these requirements (DOE, 1996a). Additional work is in progress on other waste forms. The approach described in the information need is consistent with the present Program approach.

Application of results (SCP Section 8.3.4.3.1.1)

Background and SCP Plans. This section described very briefly how the results of analyses performed for the associated information need would be used.

Changes and Status. The application of results as indicated in the SCP is consistent with the current program approach.

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Information Need 2.6.2: Design information needed to comply with preclosure criteria from 10 CFR 60.135(c) for waste forms (SCP Section 8.3.4.3.2)

Background and SCP Plans. This information need was to obtain design information to comply with preclosure criteria from 10 CFR 60.135(c) for the waste form. The section listed the specific regulatory-based parameters to be addressed and described the logic planned. Also mentioned was a requirement that high-level waste be placed in sealed containers.

Changes and Status. The approach being taken to address this information need is consistent with the approach described in the SCP. The design criteria from 10 CFR 60.135(c) address the solidification and consolidation of waste forms and the presence of combustible materials in waste forms. Analysis of each waste form to demonstrate compliance is still planned. Commercial spent nuclear fuel and defense high-level waste are in compliance, but other waste forms still require analysis. Plans to use sealed containers for each waste form or canistered waste form are still in effect.

Application of results (SCP Section 8.3.4.3.2.1)

Background and SCP Plans. This section briefly explained how information obtained to address the associated information need would be used.

Changes and Status. The application of results as indicated in the SCP is consistent with the current program approach..

Information Need 2.6.3: Waste acceptance specifications (SCP Section 8.3.4.3.3)

Background and SCP Plans. This information need was to develop specifications for acceptance at the repository of various waste forms. The section listed the parameters involved, which are acceptance specifications for unprocessed spent fuel, West Valley high-level waste, and DOE defense high-level waste. The section provided a basic logic planned to be used in addressing the information need.

Changes and Status. The present program approach is consistent with the approach presented in the information need. In addition to the waste types described in the information need, acceptance specifications will need to be developed for DOE-owned spent fuel, which has been added to the Program baseline since the SCP was written.

Application of results (SCP Section 8.3.4.3.3.1)

Background and SCP Plans. This section briefly explained how information obtained to address the associated information need would be used.

Changes and Status. The application of results as indicated in the SCP is consistent with the current program approach.

Schedule for preclosure waste package characteristics (SCP Section 8.3.4.3.4)

Background and SCP Plans. This section of the SCP provided a schedule for addressing information needs and studies for preclosure waste package characteristics.

Changes and Status. The schedule for obtaining information for many key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Program has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.4.3-2 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The Program Plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishment of major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

Issue resolution strategy for Issue 4.3: Are the waste package production technologies adequately established for the resolution of the performance issues? (SCP Section 8.3.4.4)

Background and SCP Plans. This section provided the approach to resolving the issue of whether waste package production technologies are adequately established. The approach was shown graphically in Figure 8.3.4.4-1.

Changes and Status. This section and its subsections discuss three design activities intended to show that waste packages can be produced with reasonably available technology. These activities are equally applicable to both the SCP design and the current designs. As is discussed above for Issue 2.6 (SCP Section 8.3.4.3), waste package requirements are documented in the Engineered Barrier Design Requirements Document (DOE, 1995o). Formal trade-off studies described in the SCP, in which several candidate approaches are ranked against selection criteria, have not been performed and are not planned because industrial experience with production of large, thick-walled vessels is considered sufficient to allow selection of suitable technologies. Instead, experience from production of thick-walled vessels is used to choose one or sometimes two approaches for further study. Tests on full-scale prototypes have not been performed but are still planned. Prototypes may have full-scale diameter but reduced length, because much of the length of the cylindrical part of the containment barriers will be unnecessary in demonstrating fabricability. The logic diagram for resolution of Issue 4.3 (Figure 8.3.4.4-1) is still applicable with the following modifications: The branch at the bottom of the diamond labeled "Is viable process option available?" should be removed; testing is required. As

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described previously, the step "Select fabrication process" may simply require documentation that the one candidate process is suitable.

Information Need 4.3.1: Identification and evaluation of production technologies for fabrication, closure, and inspection of the waste package (SCP Section 8.3.4.4.1)

Background and SCP Plans. This information need was to provide general information regarding identification and evaluation of waste package fabrication, closure, and inspection technologies. This section does not describe a specific strategy or process.

Changes and Status. The section is still applicable as written.

Design Activity 4.3.1.1: Waste package fabrication process development (SCP Section 8.3.4.4.1.1)

Background and SCP Plans. This design activity was to determine the processes to be used in fabricating the nonwaste form waste package components. The section listed parameters to be addressed and described planned processes.

Changes and Status. The present Program approach is different from the approach presented in the design activity, including the list of parameters. Because of their multiple containment barriers, fabrication of waste packages to current designs is more complex than fabrication to the SCP design (as discussed in this design activity). Nevertheless, the processes identified are applicable to both designs. As is noted in the Appendix A discussion for Issue 4.3 (SCP Section 8.3.4.4), selection criteria and candidate processes have not been formally developed and development is not planned. To date, the production of materials, forming and joining, heat treating, and nondestructive evaluation have been considered. Packaging, shipping, and storage as discussed in the SCP will be considered later.

Design Activity 4.3.1.2: Waste package closure process development (SCP Section 8.3.4.4.1.2)

Background and SCP Plans. This activity was to determine the final closure process for waste package containers. This section listed parameters to be addressed and described the closure process.

Changes and Status. The present Program approach differs from the approach presented in the design activity. Closure is more complicated for a multibarrier package than a single-barrier package. The greater thicknesses specified in current designs also contribute to the complexity of closure operations. As is discussed previously for Issue 4.3 (SCP Section 8.3.4.4), selection criteria and candidate processes has not been formally developed and development is not planned. Plans still state that closure will occur in a hot cell by remote control. Qualification of a welding process by monitoring process variables as discussed in the SCP is not considered practical and will not be pursued. Instead, each closure weld will be inspected.

Design Activity 4.3.1.3: Waste package closure inspection process development (SCP Section 8.3.4.4.1.3)

Background and SCP Plans. This activity was to determine the process to be used in inspecting the final closure of the waste package containers. The section listed six parameters to be addressed and briefly described the planned process.

Changes and Status. The present Program approach differs from the approach presented in the design activity. Closure inspection is as important now as when the SCP was written. As is discussed previously for Issue 4.3 (SCP Section 8.3.4.4), selection criteria and candidate processes has not been formally developed and development is not planned. Current plans are that each closure weld will be visually inspected and ultrasonically tested, both by remote means. Demonstration of these techniques is still planned.

Application of results (SCP Section 8.3.4.4.1.4)

Background and SCP Plans. This section briefly described how information from the study would be used.

Changes and Status. The application of results as indicated in the SCP is consistent with the current Program approach.

Schedule for waste package production technologies (SCP Section 8.3.4.4.2)

Background and SCP Plans. This section of the SCP provide a schedule for addressing design activities for waste package production technologies.

Changes and Status. The schedule for obtaining information for many key activities has been revised as described in the semiannual progress reports. This method of documenting changes is consistent with the text in the SCP section. The Program has not, however, undertaken to ensure the schedule revisions for all the specific items in Table 8.3.4.4-1 are included in the progress reports. The schedules presented in the 1988 SCP were based on the DOE's June 1987 Mission Plan Amendment (DOE, 1987a and b), which assumed the license application for the repository would be submitted to the NRC in 1995. In 1989, the Secretary of Energy assessed the progress and needs of the site characterization program, and a new schedule was adopted that delayed license application submittal to 2001. The Program Plan (DOE, 1994a) supporting the 2001 submittal, which was issued in December 1994, contains a schedule for accomplishment of major Program activities, but it does not explicitly revise the schedule for all SCP activities and studies. Scheduled completion dates for SCP activities may be further revised as a result of new developments in the site characterization program, changes in Program priorities, or changes in funding profiles. These changes will be discussed, as appropriate, in future progress reports; the Project, however, does not plan to necessarily address how and why each SCP schedule item has changed.

A.5 PERFORMANCE ASSESSMENT PROGRAM (SCP SECTION 8.3.5)

This section summarizes the performance assessment plans in the SCP, changes in the performance assessment program from the SCP, and the current status of that program. Performance assessment technology exists to evaluate both the preclosure radiological safety and postclosure performance of the MGDS, although considerable improvements in that technology are expected as new site data and laboratory research results become available.

Since the SCP, changes have occurred in the performance assessment program as a result of the following:

- Changes in regulatory framework, including the definition of design basis events for preclosure radiological safety and a potential radiological risk-based standard for postclosure performance
- New understanding of the site, including surface water infiltration, fracture flow, thermal-hydrological processes, and the importance of the saturated zone
- Waste package and repository design changes, principally the change to high thermal loading and from vertical borehole emplacement of small thin-walled waste packages to horizontal in-drift emplacement of very large double-walled waste packages.

Changes, if any, in the performance assessment program are reflected principally in

- The definition of design basis accidents for preclosure performance assessments
- The need to revise the approach for potential waste package retrieval
- The planned replacement of detailed technical guidelines by new system guidelines with respect to both preclosure and postclosure higher level findings and NRC siting criteria
- Increased integration of abstractions of detailed process models for postclosure performance assessments of the overall repository system and addressing the DOE's waste containment and isolation strategy
- Waste package materials being tested, including corrosion-allowance and corrosion-resistant materials, the consideration of different environmental conditions, and related model development efforts
- Minor changes in the waste form testing and related model development
- The need for remote operations for performance confirmation and shift of some activities from the site characterization phase to the post-license application period

- The availability of a suite of mathematical models and computer codes for preclosure and postclosure performance assessments, with improvements expected as new site and laboratory data become available.

A.5.1 Preclosure Performance Assessment (SCP Sections 8.3.5.1, 8.3.5.3, 8.3.5.4, and 8.3.5.5)

The four preclosure performance assessment sections of the SCP (Sections 8.3.5.1, 8.3.5.3, 8.3.5.4, and 8.3.5.5) are addressed together here because of their interdependence and because proposed NRC regulations may eliminate some of the distinctions with respect to the required evaluations.

Since the SCP was written, the NRC has proposed to refer to normal and accident events as "design basis events." The term "design basis event" is introduced in the proposed 10 CFR Part 60 rule change and is defined as follows:

1. Those natural and human-induced events that are reasonably likely to occur regularly, moderately frequently, or one or more times before permanent closure of the geologic repository operations area
2. Other natural and man-induced events that are considered unlikely, but sufficiently credible to warrant consideration, taking into account the potential for significant radiological impacts on public health and safety.

Design basis events meeting the first definition are referred to as frequency "Category 1" design basis events those meeting number 2 are classified as frequency "Category 2" design basis events. Using these definitions, "Public Radiological Exposures - Normal Conditions" (SCP Section 8.3.5.3) and "Worker Radiological Safety - Normal Conditions" (SCP Section 8.3.5.4) are Category 1 Design Basis Events, but "Accidental Radiological Releases" (SCP Section 8.3.5.5) may be Category 1 or Category 2 design basis events. As a result, normal exposures (public and worker) and accidental exposures are being grouped together (with similar models for a given category of design basis events) and radiation dose limits vary depending on the frequency category of the design basis event.

The strategy for addressing projected releases of radioactive materials to restricted and unrestricted areas and the resulting radiation exposure to the general public and workers during preclosure is addressed by "Strategy for Preclosure Performance Assessment" (SCP Section 8.3.5.1). With the impending NRC rule change regarding design basis events, this section essentially summarizes the strategy for SCP Sections 8.3.5.3, 8.3.5.4, and 8.3.5.5.

Following are summaries of the current applicability of each preclosure performance assessment SCP section and related information needs.

Strategy for Preclosure Performance Assessment (SCP Section 8.3.5.1)

Background and SCP Plans. This section addressed the development of the preclosure performance assessment strategy for resolving Key Issue 2. This issue asked whether the projected releases of radioactive materials to restricted and unrestricted areas and the resulting radiation exposures of the general public and workers during repository operation, closure, and decommissioning at Yucca Mountain would meet the applicable requirements set forth in 10 CFR Part 20, 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191.

Changes and Status. The preclosure risk assessment methodology (PRAM) program and working group described in the SCP no longer exist as formal entities. A new strategy was developed in support of the viability assessment. This strategy is documented in the Management Plan for the Development of a Project Integrated Safety Assessment (CRWMS M&O, 1996kk). The strategy considers potential regulatory changes in 10 CFR Part 60 with respect to the definition of design basis events. Where possible, the methodologies to predict the consequences of preclosure radioactive releases are being taken from previously successful license applications and environmental impact statements. A comprehensive set of candidate design basis events was defined in Preliminary MGDS Hazards Analysis (CRWMS M&O, 1996u) and also reported in the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b). FY 1997 activities will concentrate on the needs of the Project Integrated Safety Assessment in support of the viability assessment. In past analyses, the computer codes GENII, MACCS, MCNP, and DORT-TORT have been used (see Appendix Table I-1 for capabilities and references). A new biosphere radiological assessment model is being developed that will also support the postclosure radiation dose estimation and that will have the capability to evaluate long-term bioaccumulation impacts of the preclosure radioactive releases.

Public Radiological Exposures: Normal Conditions (SCP Section 8.3.5.3)

Background and SCP Plans. This section addresses Issue 2.1, which asked whether expected preclosure radiation doses received by members of the public during repository operation, closure, and decommissioning would be less than allowed by 10 CFR 60.111, 40 CFR 191 Subpart A, and 10 CFR Part 20.

Changes and Status. Efforts are in progress and will continue to demonstrate compliance with 10 CFR 60.111, 10 CFR Part 20, and the planned replacement for 40 CFR 191 Subpart A. Site data for these analyses are being collected in the site program. Atmospheric dispersion of potential release of radionuclides was modeled to assess the radiological effects of inhalation, using NRC Regulatory Guide 1.25 for guidance. The site program started a review of biosphere radiological assessment models for evaluating long-term bioaccumulation impacts of preclosure radioactive releases. The Preliminary MGDS Hazards Analysis report (CRWMS M&O, 1996u) identified a comprehensive list of possible events, both internal and external initiating events, that were then screened for relevancy to preclosure radioactive releases at the potential repository. The Source Terms for Design Basis Event Analyses report (CRWMS M&O, 1996v) presents bounding radionuclide release terms. Pilot analyses will continue for both the surface

and subsurface portions of the potential repository to evaluate whether the consequences from candidate design basis events are within regulatory limits.

Worker Radiological Safety: Normal Conditions (SCP Section 8.3.5.4)

Background and SCP Plans. This section addressed Issue 2.2, which asked whether the repository could be designed, constructed, operated, closed, and decommissioned in a manner that ensures the preclosure radiological safety of workers under normal operations as required by 10 CFR 60.111 and 10 CFR Part 20.

Changes and Status. Site data for these analyses are being collected in the site program. Radiation doses were calculated for candidate Category 1 design basis events. More candidate design basis events will be analyzed in FY 1997; some analyses will be conducted to meet specific needs for the environmental impact statement, which may be more extensive than the NRC requirements.

Accidental Radiological Releases (SCP Section 8.3.5.5)

Background and SCP Plans. This section addressed Issue 2.3, which asked whether the repository can be designed, constructed, operated, closed, and decommissioned in such a way that credible accidents do not result in projected radiological exposures of the general public and of workers in excess of applicable limiting values.

Changes and Status. Site data for these analyses are being collected in the site program. Candidate category 2 design basis events were defined in the Preliminary MGDS Hazards Analysis report (CRWMS M&O, 1996u) considering the proposed 10 CFR Part 60 rule change. The candidate design basis events are being grouped by potential radioactive release magnitude or consequence severity to identify the bounding design basis event in each group. To help identify possible issues, a small subset of the candidate design basis events is being evaluated in a pilot analysis. The Preliminary MGDS Hazards Analysis report and Source Terms for Design Basis Event Analyses report (CRWMS M&O, 1996v) were issued. The pilot analyses (surface and subsurface) to quantify the radiological consequences for the initial events considered as design basis events are expected to be issued in FY 1997.

A.5.2 Waste Retrieval (SCP Section 8.3.5.2)

Background and SCP Plans. SCP Section 8.3.5.2 addressed Issue 2.4, which asked whether the repository could be designed, constructed, operated, closed, and decommissioned so that the option of waste retrieval would be preserved as required by 10 CFR 60.111. The retrieval position and concepts presented in the SCP and supporting documents are based on vertical borehole emplacement of small waste packages at an areal thermal loading of 57 kW/acre. No further work was done with respect to retrievability until the development of the current advanced conceptual design.

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Changes and Status. Preliminary retrieval concepts are described in Section 9.2 of the MGDS Advanced Conceptual Design Report (CRWMS M&O, 1996b) and summarized in Section 6.2 of this progress report. The potential retrieval is expected to be significantly different from the SCP conceptual design of the repository and waste package (SNL, 1987) because of the change to high thermal loading, horizontal in-drift emplacement, and different canister designs.

The general five-step approach defined in the SCP for resolving Issue 2.4, however, is not expected to change. The five steps are as follows:

1. Evaluate Regulations and Data - evaluate regulatory requirements and existing site data, designs and analyses to determine what functions and processes must be performed to not preclude retrieval.
2. Allocate Performance - establish performance measures and goals (design criteria) for the processes that contribute to performing those functions.
3. Identify Retrieval Conditions - identify normal and credible abnormal conditions for retrieval-related operations and identify input items needed from Issue 4.4. (Are the technologies of repository construction, operation, closure, and decommissioning adequate established to support resolution of performance issues?; see discussion of Section 8.3.2.5 in Section A.2.2 of this appendix.)
4. Identify Input Items - identify and request site parameters necessary to meet the goals of related issues for common system elements or develop the reference preclosure repository design, operations plan, supporting analyses and demonstrations requested to support resolution of all related issues.
5. Conduct Compliance Analysis - conduct a compliance analysis to critically evaluate whether the appropriate retrieval conditions have been considered, whether the input items provided by Issue 4.4 are complete and sufficient, and whether the performance goals are met.

A retrievability study is planned in FY 1997, including the formulation of related MGDS design requirements. This study will identify scenarios using the MGDS advanced conceptual design that may require retrieval, identify retrieval options, recommend design features to facilitate retrieval, and perform a compliance analyses to determine whether Issue 2.4 can be resolved. The compliance analyses will consider the proposed NRC rule changes with respect to design basis accidents and preclosure radiological safety analyses.

The SCP approach to resolving Issue 2.4 was addressed by six information needs. The current applicability of each information need is summarized below.

Information Need 2.4.1: Site and Design Data Required to Support Retrieval (SCP Section 8.3.5.2.1)

Site data are being collected in the site program and retrieval design data will be developed after design requirements for the preliminary MGDS design (which follows the advanced conceptual design) have been formulated by the FY 1997 retrievability study.

Information Need 2.4.2: Determination that Access to the Waste Emplacement Boreholes can be Provided throughout the Retrieval Period for Normal and Credible Abnormal Conditions (SCP Section 8.3.5.2.2)

This need still exists because it addresses access from the surface facilities to the emplacement locations, although borehole emplacement is not planned. To provide access, backfill would not be placed in any area underground until after the need to maintain the retrievability option in that area will cease. The Retrieval Conditions Evaluation report (CRWMS M&O, 1995h) evaluated temperatures existing during potential retrieval operations. Ventilation to reduce temperatures and/or remotely operated retrieval may be necessary.

Information Need 2.4.3: Determination that Access to the Waste Packages can be Provided throughout the Retrieval Period for Normal and Credible Abnormal Conditions (SCP Section 8.3.5.2.3)

This need, which addresses emplacement borehole design, does not exist for the current advanced conceptual design.

Information Need 2.4.4: Determination That the Waste can be Removed from the Emplacement Boreholes throughout the Retrieval Period for Normal and Credible Abnormal Conditions (SCP Section 8.3.5.2.4)

This need, which addresses waste package and equipment design for retrieval from boreholes, still exists, although borehole emplacement is not planned. Instead, this need will be considered in the preliminary MGDS design after its design requirements for retrievability have been formulated.

Information Need 2.4.5: Determination that the Waste can be Transported to the Surface and Delivered to Waste-Handling Surface Facilities for Normal and Abnormal Conditions (SCP Section 8.3.5.2.5)

This need, which addresses the transport of waste packages from their emplacement locations to surface facilities, still exists. The need will be considered in the preliminary MGDS design after its design requirements for retrievability have been formulated.

Information Need 2.4.6: Determination that the Retrieval Requirements Set Forth in 10 CFR 60.111(b) are Met Using Reasonably Available Technology (SCP Section 8.3.5.2.6)

This generic requirement remains and will be considered in the FY 1997 retrievability study and in the preliminary MGDS design.

A.5.3 Higher Level Findings and NRC Siting Criteria (SCP Sections 8.3.5.6, 8.3.5.7, 8.3.5.17, and 8.3.5.18)

The three higher level findings sections (SCP Sections 8.3.5.6, 8.3.5.7, 8.3.5.17, and 8.3.5.18) and the NRC siting criteria section of the SCP are discussed together because of their interdependence and because proposed revisions in 10 CFR Part 960 would affect all of them in a related manner.

Higher level findings and NRC siting criteria refer to criteria in DOE and NRC regulations for assessing the acceptability of specific aspects of a candidate repository site and the acceptability of the overall performance of a repository that would be constructed at the site. The NRC siting criteria are specified in 10 CFR 60.122. These criteria are defined in terms of favorable conditions and potentially adverse conditions that must be investigated and analyzed. Higher level findings are findings with respect to qualifying conditions and disqualifying conditions that are specified by the DOE's siting guidelines in 10 CFR Part 960. These findings must be made before the DOE can recommend a site for development as a repository. The qualifying and disqualifying conditions are defined in terms of preclosure and postclosure "system guidelines" and "technical guidelines." The system guidelines specify requirements for the overall performance and characteristics of a geologic repository, and the technical guidelines identify requirements for specific attributes of the site that contribute to the overall performance and characteristics. The technical guidelines incorporate favorable conditions and potentially adverse conditions that correspond closely to the NRC's siting criteria in 10 CFR Part 60. The qualifying conditions must be satisfied for a site to be acceptable and a site is unacceptable if any of the disqualifying conditions apply.

Since the SCP was published in 1988, the regulatory framework for site selection has changed significantly. In particular, the Nuclear Waste Policy Amendments Act of 1987 (NWPAA, 1987) directed the DOE to cease characterization of two other candidate sites and to characterize the Yucca Mountain site only. This legislation rendered moot requirements in 10 CFR Part 960 for comparative site evaluations. In addition, the Energy Policy Act of 1992 (EPA, 1992) directed the EPA to develop site-specific radiation standards for the performance of a repository at Yucca Mountain and directed the NRC to conform its implementing standards in 10 CFR Part 60 with the EPA's new performance standards.

In response to the legislative changes and in consideration of the knowledge gained about the Yucca Mountain site, the DOE has prepared a draft Notice of Proposed Rulemaking to amend the general guidelines for site recommendation in 10 CFR Part 960. The amended rule would retain the existing guidelines for potential future use at other sites and would, in a new

subpart, clarify and focus the guidelines to be used in evaluating the suitability of the Yucca Mountain site. Two system guidelines would be applied to Yucca Mountain: (1) a postclosure system guideline that addresses waste containment and isolation and (2) a preclosure system guideline that addresses radiological safety. Each system guideline would have an associated qualifying condition. The DOE expects that the Notice of Proposed Rulemaking will be published in the Federal Register during the next reporting period and will enter a period of public comment and public hearings. Following resolution of the public comments, the amended regulation will be submitted to the NRC for concurrence. A final rule is expected in late FY 1997.

The work described in the SCP was organized around the resolution of a number of technical issues, including the making of higher level findings and the demonstrations required by the NRC siting criteria. The status of the work related to these issues is summarized next.

Higher-Level Findings for Preclosure Radiological Safety (SCP Section 8.3.5.6)

Background and SCP Plans. This section addressed Issue 2.5, which asked whether the higher-level findings required by 10 CFR Part 960 can be made for the qualifying condition of the preclosure radiological safety system guideline and the qualifying and disqualifying conditions of the technical guidelines for population density and distribution, site ownership and control, meteorology, and offsite installations and operations.

Changes and Status. The DOE's proposed amendment to 10 CFR Part 960 would retain, for the Yucca Mountain site, a preclosure radiological system guideline and its associated qualifying condition and would eliminate evaluation of specific technical guidelines. However, the information required to assess compliance with the technical guidelines would have to be collected and analyzed to assess compliance with the system guideline. Assessment of compliance with 10 CFR Part 960 is scheduled for completion in FY 1999.

Higher Level Findings for Ease and Cost of Construction (SCP Section 8.3.5.7)

Background and SCP Plans. This section addressed Issue 4.1, which asked whether higher level findings could be made for the preclosure system guideline for ease and cost of siting, construction, operation, and closure and for the qualifying and disqualifying conditions of the technical guidelines for surface characteristics, rock characteristics, hydrology, and tectonics. The guidelines of this section address whether construction of a repository is technically feasible, based on reasonably available technology, and whether repository costs would be reasonable in comparison with other siting options.

Changes and Status. Under the proposed amendments to 10 CFR Part 960, no findings would be required for these guidelines for the Yucca Mountain site. Technical feasibility would be addressed implicitly in the design process. The comparative cost criterion was rendered moot by the Nuclear Waste Policy Amendments Act of 1987.

NRC Siting Criteria (SCP Section 8.3.5.17)

Background and SCP Plans. This section addressed Issue 1.8, which asked whether demonstrations for favorable and potentially adverse conditions could be made as required by 10 CFR 60.122.

Changes and Status. These demonstrations must be included in the license application, currently scheduled for completion in FY 2002.

Higher Level Findings for Postclosure System and Technical Guidelines (SCP Section 8.3.5.18)

Background and SCP Plans. This section addressed Issue 1.9, which asked whether higher level findings could be made for the postclosure system guideline for waste containment and isolation and the qualifying and disqualifying conditions of the technical guidelines for geohydrology, geochemistry, rock characteristics, climatic changes, erosion, dissolution, tectonics, and human interference.

Changes and Status. The proposed amendments to the siting guidelines would, for the Yucca Mountain site, retain a postclosure system guideline for waste containment and isolation and an associated qualifying condition and would eliminate evaluation of specific technical guidelines. However, the information addressed in the technical guidelines will be integrated into the total system performance assessments that the DOE will conduct to evaluate compliance with the postclosure system guideline.

A.5.4 Postclosure Performance Assessment and Pre-Waste-Emplacement Ground-Water Travel Time (SCP Sections 8.3.5.8, 8.3.5.12, 8.3.5.13, 8.3.5.14, and 8.3.5.15)

The principal postclosure performance assessment sections and the pre-waste emplacement ground-water travel time section of the SCP (Sections 8.3.5.8, 8.3.5.12, 8.3.5.13, 8.3.5.14, and 8.3.5.15) are covered together because of their interdependence and because the revised total system performance assessment approach addresses them in an integrated manner.

Since the issuance of the SCP, two major changes have occurred. The first change had been driven by the expected changes in regulatory performance measures and the second by a change in philosophy.

The primary change in the expected regulatory criteria is from a radionuclide release-based standard to a radiation dose-based standard. In this instance, the final representation changes from a complementary cumulative distribution function of radionuclide release to some measure of radiation dose to an individual or population. From a performance assessment standpoint, this also changes the relative importance of certain components of the total system (such as the increased importance of the details of the saturated zone). From an analysis standpoint, the primary change would be the need for analyses tools for the prediction of radiation doses from all

potential pathways (only drinking water ingestion and carbon-14 inhalation needed to be analyzed previously) and the analysis of biosphere radionuclide transport and radiation exposures to humans.

The overall postclosure performance assessment approach has moved from using a suite of different and uncoupled mathematical models and computer codes to assess the various subsystem and total system requirements to a more integrated approach. The interdependence of the various processes important to performance still requires that each of the subsystem requirements be assessed in the context of the total system. For instance, the radionuclide releases from the waste package are completely dependent upon the evolution of the nonisothermal ground-water flow field. The current plan is to develop a single total system performance tool. This tool will reflect the current understanding of the site and design using alternative conceptual models and parameter distributions that reflect both their variability and uncertainty. A set of model abstraction and testing activities are in progress that will develop the mathematical representation for each important process within the total system. These activities (listed below) will then be synthesized into the total system analysis tool.

To address any subsystem or total system performance measure, the appropriate analyses will be run as a part of the total system performance assessment to preserve the integrity of the process interdependencies. The results for each subsystem will simply be pulled from the appropriate point within the total system analyses. For the ground-water travel time, work on fast path flow has been explicitly incorporated in the development of the unsaturated and saturated zone flow and transport elements (Ho et al., 1996). Both pre-waste emplacement ground-water travel time and post-waste emplacement ground-water travel time have been assessed and reported previously (Arnold et al., 1995; Altman et al., 1996a). These specific analyses can be updated in the context of work on relevant processes in the context of the total system analyses development.

The postclosure performance assessment approach just described has been developed through iterative total system performance assessments in 1991 (Barnard et al., 1992; Eslinger et al., 1993), 1993 (Andrews et al., 1994; Wilson et al., 1994), and 1995 (CRWMS M&O, 1995a), testing of model abstractions (CRWMS M&O, 1996pp), and scenario development (Barr et al., 1996).

The next postclosure performance assessment iteration for the overall MGDS system will be in FY 1997 in support of the viability assessment. The major activities for this purpose will be as follows (CRWMS M&O, 1996ii):

- Scenario development
- Unsaturated zone flow testing and abstraction
- Unsaturated zone transport testing and abstraction
- Saturated zone flow and transport testing and abstraction
- Thermohydrologic flow testing and abstraction
- Waste package degradation testing and abstraction
- Waste form degradation testing and abstraction

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- Waste form mobilization testing and abstraction
- Near-field environment testing and abstraction
- Biosphere testing and abstraction
- Disturbed processes testing and abstraction
- Total system performance assessment tools and methodology
- Performance assessment support to design
- Performance assessment support to site
- Performance assessment support to oversight and other external interactions.

Following are summaries of the current applicability of each postclosure performance assessment and the pre-waste emplacement ground-water travel time SCP section and related information needs.

Strategy for Postclosure Performance Assessment (SCP Section 8.3.5.8)

Background and SCP Plans. This section addressed the development of the postclosure performance assessment strategy for resolving Key Issue 1. This issue asked whether the MGDS at Yucca Mountain would isolate the radioactive waste from the accessible environment after closure in accordance with the requirements of 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191.

Changes and Status. Postclosure performance assessment activities have been revised in anticipation of possible new EPA standards for a potential repository at Yucca Mountain. The current strategy is defined in the Total System Performance Assessment - Viability Assessment (TSPA-VA) Plan report (CRWMS M&O, 1996ii), which is based on the waste containment and isolation strategy (DOE, 1996o), total system performance assessments conducted to date (Barnard et al. 1992; Eslinger et al., 1993; Andrews et al., 1994; Wilson et al., 1994; CRWMS M&O, 1995a), the Description of Performance Allocation (CRWMS M&O, 1996hh), and numerous other Project reports (summarized in Chapter 6 of this and previous progress reports).

Ground-Water Travel Time (SCP Section 8.3.5.12)

Background and SCP Plans. This section addressed Issue 1.6, which asked whether the site will meet the performance objective for pre-waste-emplacement ground-water travel time as required by 10 CFR 60.113.

Changes and Status. A comprehensive analysis of pre-waste-emplacement ground-water travel time has been completed (Altman et al., 1996a), and no new analyses are planned because of expected changes in the NRC regulations. Post-waste-emplacement ground-water travel time analyses will continue as new site data are collected and the MGDS design evolves to evaluate thermal-hydrological regime in support of postclosure performance assessments of the overall repository system.

Total System Performance (SCP Section 8.3.5.13)

Background and SCP Plans. This section addressed Issue 1.1, which asked whether the MGDS would meet the system performance objective for limiting radionuclide releases to the accessible environment as required by 10 CFR 60.112 and 40 CFR 191.13.

Changes and Status. Analyses, including potentially disruptive scenarios, have been included in past iterations of postclosure performance assessments of the overall repository system. Although analyses of radionuclide transport to the accessible environment will continue if a radiological risk based standard is adopted, the integration of radionuclide release over the boundary of the accessible environment for 10,000 years and the calculation of an empirical complementary cumulative distribution function would no longer be needed.

Individual Protection (SCP Section 8.3.5.14)

Background and SCP Plans. This section addressed Issue 1.2, which asked whether the MGDS would meet the requirements for limiting individual radiation doses in the accessible environment for 1000 years after waste disposal as required by 40 CFR 191.15.

Changes and Status. The analyses of radiation doses from drinking contaminated water and from carbon-14 releases will become a component of the calculation of postclosure radiological risk from all environmental pathways if a radiological risk standard is adopted. The most recent calculations of radiation doses from drinking water and carbon-14 were included in the 1993 total system performance assessment (Andrews et al., 1994; Wilson et al., 1994).

Ground-Water Protection (SCP Section 8.3.5.15)

Background and SCP Plans. This section addressed Issue 1.3, which asked whether the MGDS would meet the requirements for the protection of special sources of ground water for 1000 years after waste disposal as required by 40 CFR 191.16.

Changes and Status. The analyses of radionuclide concentrations in the ground water of the saturated zone in the accessible environment will become a component of the calculation of postclosure radiological risk from all environmental pathways if a radiological risk standard is adopted. The most recent calculations of radionuclide concentrations in the ground water of the saturated zone in the accessible environment were included in the 1993 total system performance assessment (Andrews et al., 1994; Wilson et al., 1994).

A.5.5 Containment by Waste Package/Waste Package Materials Testing and Model Development (SCP Section 8.3.5.9)

The SCP consisted of activities that addressed Issue 1.4, which asked whether the waste package would meet the performance objective for containment as required by 10 CFR 60.113. The SCP objective for Issue 1.4 was to "provide total containment of the enclosed waste for the

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containment period under anticipated repository conditions recognizing technological limitations and residual uncertainties." The SCP noted that "the performance of the waste package during the containment period would be best achieved by minimizing the residual uncertainties. The residual uncertainties in predicting performance are caused by several factors: (a) the inherent limitations associated with manufacturing, handling, and emplacement operations, (b) the uncertainty in developing a complete understanding of the behavior of waste package materials, and (c) the uncertainty in predicting the future environment of each waste package." Accordingly, this issue is closely coupled with Issue 4.3 (Are the waste package production technologies adequately established for the resolution of the performance issues?) and Issue 1.10 (Have the characteristics and configurations of the waste packages been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.135, and (b) provide information for the resolution of performance issues?). Issues 4.3 and 1.10 are discussed in Section 8.3.4.4 and 8.3.4.2, respectively, of Section A.4 of this appendix.

The approach to resolving Issue 1.4 was described within the logic of five information needs: (1) waste package design features that affect the performance of the container, (2) material properties of the container, (3) scenarios and models needed to predict the rate of degradation of the container material, (4) estimates of the rates and mechanisms of container degradation in the repository environment for anticipated and unanticipated processes and events, and calculation of the failure rate of the container as a function of time, and (5) determination of whether the set of waste packages meets the performance objective for substantially complete containment for anticipated processes and events. A summary of the current status and any changes for these information needs follows.

Although the waste package design concept has been modified from single barrier container approach [SCP Conceptual Design Report (SNL, 1987)] to the current multiple barrier approach [advanced conceptual design phase (CRWMS M&O, 1996b)], considerable linkage still exists between the SCP and the current metal barriers selection and test program. SCP Issue 1.4 and its information needs remain fundamentally unchanged. The current waste package container designs include families of materials other than the copper-base materials and the iron to nickel-base "austenitic" materials that were the subject of the SCP Conceptual Design. Of the candidate materials identified in the SCP, only nickel-base Alloy 825 (ASTM B 424 N08825) and copper-nickel Conceptual Design Analysis 715 (ASTM B171) remain among candidates for the advanced conceptual design evaluations. The testing and modeling program has been expanded to encompass corrosion allowance, corrosion resistant, and intermediate materials, and the test environments have been expanded to bracket the range of temperatures and environments that may be encountered for the different waste package and repository design options.

The SCP mentioned that "alternative" designs, including multiple metallic barriers, might be considered, but it did not discuss which materials and how they might be configured. While many of the same individual corrosion degradation modes discussed in the SCP apply to multiple barrier containers, the interaction among the barriers, which is so important to overall performance, is a major element of the current program that was not foreseen in the SCP. Accordingly, the testing and modeling work has been moved from the single-metal system activities to bimetallic system activities, which address not only individual degradation

mechanisms, but also the interactions between the outer corrosion allowance barrier and the inner corrosion resistant barrier.

The performance modeling activities for the calculation of waste package containment times and the determination of whether the set of waste packages meets the performance objective remain consistent with the approach described in SCP Sections 8.3.5.9.4 and 8.3.5.9.5. The following sections have been moved to the design sections: SCP Section 8.3.5.9.1.1, Integrate Design and Materials Information (Metal Container), Subactivities 1.4.1.1.4 and 1.4.1.1.5, dealing with state of stress and weld integrity, and SCP Section 8.3.5.9.1.2, Integrate Design and Materials Information (Alternate Barriers Investigations), Subactivity 1.4.1.2.5, dealing with nondestructive characterization.

Changes to the metal barrier selection and testing program result primarily from major changes in the technical scope of the waste package activities that have occurred in the advanced conceptual design phase of the Project. In particular, the shift from the SCP conceptual design single barrier container to the advanced conceptual design multiple barrier concept has resulted in a more "robust" waste package, comprising two or more metallic barriers, as well as additional engineered barriers, that might better be demonstrated to meet the containment objectives.

The SCP conceptual waste package design is described in the SCP Conceptual Design Report (SNL, 1987). The multiple-barrier approach to waste package container designs is discussed in the Controlled Design Assumptions Document (CRWMS M&O, 1996e) and the "bimetallic" option currently being pursued is described in the Advanced Conceptual Design Report (CRWMS M&O, 1996b). The Metal Barrier Selection and Testing Program Scientific Investigation Plan (McCright, 1996) documents the changes to SCP Sections 8.3.5.9.1 through 8.3.5.9.3, in response to the advanced conceptual design multibarrier approach to waste package containers. Results from the activities completed to date in this investigation are documented in the Engineered Materials Characterization Report (McCright, in prep.)

A.5.6 Engineered Barrier Release Rates/Waste Form Testing and Model Development (SCP Section 8.3.5.10)

The SCP approach consisted of activities that addressed Issue 1.5, which asked whether the waste package and the engineered barrier system would meet the performance objective for radionuclide release rates as required by 10 CFR 60.113. The activities include waste form characterization, alteration, dissolution, and radionuclide release, as well as model development and utilization to determine compliance.

The current approach is essentially the same as that given in the SCP. The current effort is detailed in scientific investigation plans and the Waste Form Characteristics Reports (Stout and Leider, 1994; Stout et al., 1996) for the waste form testing and modeling. Related performance assessment activities are given in companion documents. Most of the changes deal with deferring activities because of funding considerations or by reduced need for the activity

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indicated by information collected to date. The following discusses the five information needs and the changes, if any, between the SCP and the current approach.

Information Need 1.5.1: Waste Package Design Features that Affect Radionuclide Release (SCP Section 8.3.5.10.1)

The activity for this information need deals with integration of waste form data. The activity is essentially the same as planned in the SCP except that the vehicle for information transfer has become the Controlled Design Assumptions Document (CRWMS M&O, 1996e) and the Waste Form Characteristics Reports (Stout and Leider, 1994; Stout et al., 1996), rather than the Spent Fuel Working Group described in the SCP. The Spent Fuel Working Group is no longer active.

Information Need 1.5.2: Material Properties of the Waste Form (SCP Section 8.3.5.10.2)

The two activities for this information are (1) characterization of the spent nuclear fuel waste form and (2) characterization of the high-level waste glass forms. These activities address dissolution and oxidation of spent nuclear fuel, zircaloy, hardware and carbon-14 release, and leaching of high-level waste glass. The current program has focused on testing spent nuclear fuel and high-level waste glass. The testing of hardware and carbon-14 has been deferred until FY 1998. The failure of zircaloy cladding is being evaluated this fiscal year; the experimental effort, however, if needed, has been deferred until FY 1998. There has been no cooperative testing with waste producers, as planned in the SCP, and none is planned.

Information Need 1.5.3: Scenarios and Models Needed to Predict the Rate of Radionuclide Release from the Waste Package and Engineered Barrier System (SCP Section 8.3.5.10.3)

The five activities for this information need are (1) the integration of scenarios for radionuclide releases from the waste packages, (2) the development of a geochemical speciation and reaction model, (3) the development of models for radionuclide release from the spent nuclear fuel, (4) the development of models for radionuclide release from the high-level waste glass forms, and (5) the development of waste package performance assessment models. Scenarios for waste package criticality have been developed as part of the waste package development efforts. There has been little other work on scenario and related model development, with the exception of water contact and radionuclide release mechanism assumptions made in the total system performance assessments (Barnard et al., 1992; Eslinger et al., 1993; Andrews et al., 1994; Wilson et al., 1994; CRWMS M&O, 1995a). Future work will be performed as part of total system performance assessments, including in support of the viability assessment. Also included is the development of the thermodynamic data base GEMBOCHS and the geochemical computer code EQ3/6 (Daveler and Wolery, 1992; Wolery, 1992a and b; Wolery and Daveler, 1992). The GEMBOCHS work has concentrated on augmenting the data base with data from worldwide sources as they become available. Recent EQ3/6 modeling work has been limited and focused on simulating geochemical speciation and the behavior of spent nuclear fuel and high-level waste glass. The GEMBOCHS and EQ3/6 activities closely follow the plan in the SCP. Detailed mathematical models are being developed

for waste form dissolution and radionuclide release from spent nuclear fuel and high-level waste glass on the basis of the experimental results. These detailed models are synthesized in the engineered system performance assessment computer code YMIM (Gansemer and Lamont, 1995), the waste package performance assessment code AREST (Liebetrau et al., 1987, Buxbaum and Engel, 1991; Engel and McGrail, 1993), and the waste package degradation computer code WAPDEG (Atkins and Lee, 1996; Lee et al., 1996a).

Information Need 1.5.4: Determination of the Release Rates of Radionuclides from the Waste Package and Engineered Barrier System for Anticipated and Unanticipated Events and Processes (SCP Section 8.3.5.10.4)

The two activities for this information are (1) deterministic and (2) probabilistic calculations of radionuclide releases from the waste packages. The current work closely follows the plan in the SCP. Recent analyses of releases have been part of total system performance assessments (Barnard et al., 1992; Eslinger et al., 1993; Andrews et al., 1994; Wilson et al., 1994; CRWMS M&O, 1995a). Scoping analyses are conducted in support of the waste form and waste package barrier experimental work and in support of waste package development.

Information Need 1.5.5: Determination of the Amount of Radionuclides Leaving the Near-Field Environment of the Waste Package (SCP Section 8.3.5.10.5)

The two activities for this information need are (1) the determination of radionuclide transport parameters and (2) radionuclide transport modeling in the near-field environment. More specifically, these two activities involve (1) experimental measurements of radionuclide distributions in tuff wafers and cores and (2) near-field radionuclide transport model validation and applications. Previous experimental work is documented in the Near-Field and Altered-Zone Environment Report (Wilder, 1996); no new experimental work is planned. Radionuclide transport parameter research is also part of the site program. There has been no model validation other than that the detailed process models are based on experimental results. Model applications include sensitivity studies, support of engineered barrier system studies, and components of total system performance assessments.

A.5.7 Seal Performance (SCP Section 8.3.5.11)

SCP Section 8.3.5.11 addresses whether the design of the seal system will meet the requirements of 10 CFR 60.134(a) and (b) and how seal performance will contribute to the engineered barrier system performance in accordance with 10 CFR 60.113(a)(1). The seal system is defined as being composed of shafts, ramps, exploratory boreholes and their seals, and the sealing components of the underground facility.

The overall goals of sealing have not changed, which are to (a) minimize water flow to the waste packages through man-made openings in the host rock, (b) minimize gaseous radionuclide releases to the ground surface through these openings, and (c) minimize aqueous radionuclide transport from the waste packages to the saturated zone through these openings. Preliminary

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analyses of seal performance, seal test planning, and evaluations of sealing components have been completed (Fernandez, 1985; Fernandez et al., 1987; Fernandez et al., 1993). Because of uncertainties in new regulations for postclosure MGDS performance, the goals and performance measures listed in the SCP, however, may no longer be relevant. Consequently, the seal performance goals, the possibility to seal selectively with respect to needed seal performance and locations, and the need to seal at all from a postclosure performance standpoint have to be revisited.

A systems study is in progress that will identify how components of the sealing systems will meet the expected regulations and what additional work will need to be performed before licensing. Pending the results of this study, additional work on seals has been deferred. A substantial portion of the sealing design information was not intended to be developed until the performance confirmation period. Sealing of boreholes is possibly the exception because some boreholes may be sealed before the repository becomes operational.

Additional detail is provided in the Repository section of this appendix that addresses SCP Investigation 8.3.3.2.2 (materials and characteristics of seals for shafts, drifts and boreholes).

A.5.8 Performance Confirmation (SCP Section 8.3.5.16)

SCP Section 8.3.5.16 addressed Issue 1.7 on performance confirmation, which was directly related to the performance confirmation program requirements of 10 CFR 60.137 and Subpart F (consisting of Sections 60.140 through 60.143).

The SCP (DOE, 1988) described preliminary plans for a performance confirmation program that would encompass two major phases: (1) the baseline phase and (2) the confirmation phase. The submittal of the license application marks the division between the two phases.

The baseline phase would consist of acquiring and developing information during site characterization. This phase would include (a) developing information on subsurface conditions and natural systems important to the performance assessment to be provided in the license application and those aspects of design integral to the assessment and (b) monitoring and analyzing changes in this baseline information as a result of site characterization and predicting changes resulting from construction and operation.

The confirmation phase would consist of in situ monitoring, laboratory and field testing, and associated analyses required to confirm (a) assumptions regarding the actual subsurface conditions at the site, and (b) the functioning of the engineered and natural systems and components as predicted by the performance assessment calculations presented in the license application.

A subset of the testing conducted during site characterization would provide the baseline data needed for performance confirmation. In Tables 8.3.5.16-1 and 8.3.5.16-2, the SCP listed specific monitoring and testing activities planned during site characterization and testing activities planned to be continued for performance confirmation. These activities were not intended to be complete, but rather to indicate the monitoring and testing tentatively identified at that time as being useful for performance confirmation.

Preliminary plans for the performance confirmation program have been documented in the Performance Confirmation Concepts Study Report (CRWMS M&O, 1996jj). There is little difference between the overall approach and the testing, measurement, monitoring, observation, and evaluation concepts identified in this report and the SCP. Some differences exist because the SCP addressed an Exploratory Shaft Facility in contrast to the ESF being built. Most of the parameters and most of the monitoring and testing activities listed in the SCP are identified as performance confirmation parameters and concepts in the referenced study. The comparison of specific activities is not complete, however, because the referenced study was limited to identifying concepts that significantly affect the MGDS design (that is, principally activities in underground excavation, including the ESF and potential repository). Other concepts, such as surface-based monitoring that does not significantly influence the MGDS design, will be identified in a follow-up of the referenced study.

A.5.9 Essentially Completed Analytical Techniques and Analytical Techniques Requiring Significant Development (SCP Sections 8.3.5.19 and 8.3.5.20)

The SCP sections on essentially completed analytical techniques and on analytical techniques requiring significant development are covered together because of their interdependence and because techniques are available now for all processes to be modeled for a potential repository at Yucca Mountain (although model development and improvements are not yet completed as mentioned below and in other sections of this progress report).

The SCP defined "essentially completed analytical techniques" as "those that already exist and could be used, with little additional work or only minor modifications, to conduct performance assessment analyses." This included computer codes that have not yet been fully verified and mathematical models that have not yet been validated for application to the conditions at Yucca Mountain. Analytical techniques requiring significant development were "those for which analysis approaches are still being formulated, solution methods are still being developed, or codes are still being written or tested." The SCP listed computer codes considered essentially completed at the time the SCP was written. Appendix I of this progress report lists computer codes that have been used by the Project in the past, are being used at present, and that remain candidates for future use. Some of the computer codes listed in the SCP have been dropped in favor of others that reflect advances in (a) understanding the conditions at Yucca Mountain, (b) engineering design methods, (c) numerical analyses techniques, and (d) computer hardware capabilities.

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Appendix Table I-1 also indicates (with an asterisk) which computer codes and versions have been approved for use in activities subject to the Quality Assurance Requirements and Description (DOE, 1995d). These computer codes can be used for ESF and MGDS design and for performance assessments in support of a license application. To date, this has included principally computer codes that are being used in the ESF and MGDS design; most of these are proprietary codes acquired from commercial vendors. Only a few of the computer codes currently being used for performance assessments and related analyses have been approved for use in activities subject to the Quality Assurance Requirements and Description.

Approval of computer codes for use in activities subject to the Quality Assurance Requirements and Description requires verification of the computer codes and control of the use of the codes in accordance with quality assurance procedures that implement the Quality Assurance Requirements and Description. This approval does not require validation of the mathematical models in the computer codes. According to the SCP, "verification studies are used to demonstrate that the numerical values produced by a computational procedure correspond to the mathematical formulas on which they are based." No change has occurred in this approach.

No documented plan exists at present for mathematical model validation. To date, the approach has been generally to develop new mathematical models in parallel with experimental work (e.g., waste form and waste package barrier degradation models) and to attempt to replicate laboratory and field measurements with existing models (e.g., ground-water flow and contaminant transport models, including coupled thermal-hydrological models). This approach is considered adequate to establish the validity of the mathematical models.

Future model development will consist principally of (a) improving the currently used detailed process models to better represent conditions at Yucca Mountain as new site and laboratory data become available, (b) developing new models to fill gaps identified by the new information, (c) abstracting simplifications of the detailed process models for use in total system performance assessments, and (d) integrating the abstractions into the total system performance assessment approach and software. This process is documented in the total system performance assessment plan for the viability assessment (CRWMS M&O, 1996ii).

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APPENDIX B

Regulatory and Management Document Progress

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APPENDIX B

Regulatory and Management Document Progress

This appendix summarizes in tabular form the status of selected important regulatory and management documents related to the Yucca Mountain Site Characterization Project. Progress on each document since the last progress report is described, followed by a forecast of future activity related to that document. Documents discussed include various engineering requirements documents, the Site Design and Test Requirements Document, the Project and Environmental Management Plans, and the Systems Engineering Management Plan. Other plans and documents are also discussed.

A number of comments are currently on hold pending resolution of the document hierarchy. The hierarchy will be streamlined in FY 1997 to: (a) reduce the cost of maintaining the technical baseline documentation, (b) structure the technical baseline to be more in line with the program/project management model, (c) provide a technical baseline that is structured to be more responsive to implementing changes, and (d) simplify traceability. The results of the hierarchy change on affected documents will be reflected next reporting period.

Documents cited in this appendix are included in the consolidated reference list for this progress report (Appendix L).

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Table B-1. Regulatory and Management Document Progress

Document	Progress or Change	Forecast
Regulatory Documents		
Mined Geologic Disposal System Requirements Document (DOE, 1996c)	Document change notice completed to accommodate a variety of cask/canister systems for spent nuclear fuel in addition to the multi-purpose canister. Another document change notice is in progress to incorporate U.S. Department of Energy (DOE) spent nuclear fuel. A Base-line Change Proposal has been approved to move this document from the Program level to the Project level when the Civilian Radioactive Waste Management System Requirements Document, Revision 3, and the Mined Geologic Disposal System Requirements Document, Revision 2, DCN 2, are approved.	Complete the document change notice to incorporate DOE spent nuclear fuel. No additional revisions planned pending resolution of the document hierarchy which is discussed in Section 2.1.3 of this progress report.
Repository Design Requirements Document (DOE, 1994f)	Revision placed on hold to incorporate the multipurpose canister changes from the revised Mined Geologic Disposal System Requirements Document and to allocate requirements to repository configuration items.	On hold pending resolution of the document hierarchy.

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Document	Progress or Change	Forecast
Engineered Barrier Design Requirements Document (DOE, 1995o)	Revision placed on hold to incorporate the multipurpose canister changes from the revised Mined Geologic Disposal System Requirements Document and to allocate requirements to engineered barrier configuration items.	On hold pending resolution of the document hierarchy
Site Design and Test Requirements Document (DOE, 1995p)	Interim change notice completed to remove test objectives. The test objectives will be baselined in individual study plans.	On hold pending resolution of the document hierarchy.
Exploratory Studies Facility Design Requirements (DOE, 1996p)	Revision completed to provide detailed interpretation of the applicable 10 CFR Part 60 requirements for the design of the Exploratory Studies Facility (ESF), to provide the allocation of each ESF design requirement to each configuration item, and to address changes in the Site Design and Test Requirements Document.	On hold pending resolution of the document hierarchy.
Surface-Based Testing Facilities Requirements Document (DOE, 1996q)	No additional revisions completed in fiscal year (FY) 1996.	On hold pending resolution of the document hierarchy.
Controlled Design Assumptions Document (CRWMS M&O, 1996e)	Revision completed to delete the functional analysis and the concept of operations and incorporate changes to the technical baseline during FY 1996.	Revision planned to incorporate changes to the technical baseline during the first half of FY 1997.

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Document	Progress or Change	Forecast
Site Characterization Program Baseline (DOE, 1995g)	In FY 1996, Revision 14 of the Site Characterization Program Baseline was issued for technical review. The review of Revision 14 has been canceled pending resolution of the document hierarchy. See Appendix H of this progress report for a history of changes to the Site Characterization Program Baseline.	On hold pending resolution of the document hierarchy.
Management Documents		
Project Management Plan (DOE, 1995q)	Revision completed to capture current Project organizations and relationships, reflect 1994 Program Plan, and incorporate new project management process model.	No revision is planned.
Environmental Management Plan (DOE, 1993c)	Revision under review.	Review scheduled for completion during FY 1997.
Project Work Breakdown Structure (DOE, 1995r)	Minor changes made to reflect the current Program direction.	No revision planned. Minor changes will be made as necessary during fiscal year planning.
Systems Engineering Management Plan (DOE, 1994h)	No change.	No revision planned.

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APPENDIX C

Project Change Control Board Actions

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APPENDIX C

Project Change Control Board Actions

This appendix summarizes significant Change Control Board actions to the Project Baseline and the Project Cost and Schedule Baseline.

Proposed changes to quality affecting and nonquality affecting documents listed in the Change Control Board Register are submitted using a Change Request in accordance with procedure YAP-3.5Q, Change Control Process. A Change Request is reviewed, and if acceptable in form and content, is processed by Configuration Management; evaluated by the Change Control Board Members; and dispositioned by the Change Control Board Chairperson. A Directive is issued with instructions that the change be implemented by affected organizations in accordance with corresponding procedures.

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Requirements and Management Document Changes

Title	Change Description/Disposition	Status
Revise the Site Design and Test Requirements Document (DOE, 1995)	Remove the Site Characterization Test Objectives from the Site Design and Test Requirements Document. Studies and activities are not requirements and should not be in a requirements document.	Closed
Mined Geologic Disposal System Requirements Document (DOE, 1995)	Transfer Change Control authority for the Mined Geologic Disposal System Requirements Document from the Program Baseline Change Control Board to align Project responsibility/work scope. This change was endorsed to the Program Baseline Change Control Board for approval.	Closed

Exploratory Studies Facility Changes

Title	Change Description/Disposition	Status
Continuation of Tunnel Boring Machine Operations	Authorizes continuation of the Exploratory Studies Facility tunnel boring machine full operations, as well as acceleration of associated design products and procurement of materials necessary to maintain tunnel boring machine operations to "hole" through.	Closed
Addition of Scientific Workscope to support Tunnel Boring Machine Operation beyond Station 39 + 40 (3940 m)	Scientific Investigation Schedule modified to support the tunnel boring machine advancement beyond Station 39 + 40 (3940 m). This new schedule will allow acceleration of testing on the northern Ghost Dance fault geothermal borehole.	Closed

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Cost Schedule and Work Scope Changes

Title	Change Description/Disposition	Status
Revise fiscal year (FY) 1996 Project Cost and Schedule Baseline for Work Breakdown Structure 1.2.5.7	Revised work scope and deliverables to incorporate activities related to regulatory reform and development of the waste containment and isolation strategy.	Closed
Modify FY 1996 Baseline in Support of Development of the Long-Range Plan	Added the binning of systems, structures and components; added Civilian Radioactive Waste Management System Requirements Document revision support and development of the Mined Geologic Disposal System Design Requirements Document; added support for the Project Integrated Safety Assessment development; reduced Mined Geologic Disposal System Concept of Operations scope; deleted "stop work" on the Repository Design Requirements Document and Site Characterization Program Baseline.	Closed
Revise the Project Cost and Schedule Baseline	Revised the Project Cost and Schedule Baseline to include detailed cost history for FY 1993-1995, as well as updated projections for FY 1996-2002. Also revised milestone and schedule data. This change is based on the provisions of the Program Plan.	Closed

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APPENDIX D

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations

APPENDIX D

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations

This appendix documents interactions among the U.S. Department of Energy (DOE) and other organizations associated with the Yucca Mountain Site Characterization Project. Most of these interactions are held for the purpose of communicating with the U.S. Nuclear Regulatory Commission (NRC) or the Nuclear Waste Technical Review Board (NWTRB). Other interested parties, such as the State of Nevada, frequently participate in these interactions with the NRC and the Board.

Appendix D consists of a table that shows interactions that occurred during the six-month reporting period of this progress report, including the following:

- Organization with whom the interaction occurred
- Date of the interaction
- Location of the interaction
- Type of interaction (Technical Exchange, Management Meeting, etc.)
- Short summary of the subject and purpose of each interaction.

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations

Organization	Date	Type	Location	Subject/Purpose
NRC	4/23/96	Appendix 7 Meeting	San Antonio, Texas	Discuss DOE's planned seismic design methodology and revisions to Seismic Topical Report II.
NRC	5/7-8/96	Appendix 7 Meeting	Southwest Research Institute, Texas	Exchange information on various conceptual tectonic models applicable to Yucca Mountain.
NRC	5/8/96	Management Meeting	Washington, DC and Las Vegas, Nevada (video conference)	Provide a forum for DOE and NRC managers to discuss current activities, concerns and resolve identified issues.
NRC	5/22-23/96	Technical Exchange	Las Vegas, Nevada	Discuss the results of selected aspects of NRC staff and Center for Nuclear Waste Regulatory Analyses staff review of the DOE's Total System Performance Assessment - 1995.
NRC	6/3/96	Technical Meeting	Washington, DC and Las Vegas, Nevada (video conference)	Identify issues, propose resolutions, and resolve issues related to the design, testing, and construction of the Exploratory Studies Facility (ESF).
NRC	7/1/96	Management Meeting	Washington, DC and Las Vegas, Nevada (video conference)	Provide a forum for DOE and NRC managers to discuss current activities, concerns, and for resolution of identified issues.
NRC	7/24/96	Appendix 7 Meeting	Las Vegas, Nevada	NRC site visit of thermal test alcove and discussion of excavation methods and their impact on the results of thermal tests.

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations (continued)

Organization	Date	Type	Location	Subject/Purpose
NRC	8/15/96	Technical Exchange	Washington, DC and Las Vegas, Nevada (video conference)	Explain replanning of the Site Characterization Program. Discuss context, goals, and integration of long range planning. Provide insight about Program planning to 2002.
NRC	9/10/96	Appendix 7 Meeting	Las Vegas, Nevada	Discuss DOE's Probabilistic Volcanic Hazard Assessment process and documentation; NRC's comments on the Probabilistic Volcanic Hazard Assessment and expert elicitation process; and determine areas of improvement for future expert elicitation.
NRC	9/12/96	Technical Meeting	Washington, DC and Las Vegas, Nevada (video conference)	Identify issues, propose resolutions, and resolve issues related to the design, testing, and construction of the ESF.
NRC's Advisory Committee on Nuclear Waste (ACNW)	5/15/1996	83rd ACNW Meeting	Rockville, Maryland	Discussion of items of current interest related to the NRC's Division of Waste Management programs including progress at the Yucca Mountain site, issue resolution process, status of NRC Key Technical Issues, and documentation of DOE's decisions related to Project activities.
ACNW	6/25-26/1996	84th ACNW Meeting	Rockville, Maryland	Discussion of the critical group and reference biosphere for use in dose calculations, a review by the NRC staff of DOE's Total System Performance Assessment - 1995, and a presentation by DOE on the revised Program Plan for Yucca Mountain.

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations (continued)

Organization	Date	Type	Location	Subject/Purpose
ACNW	8/21-22/1996	85th ACNW Meeting	Rockville, Maryland	A workshop and discussion of NRC activities related to coupled processes that could affect preclosure and postclosure performance at Yucca Mountain, and discussion of the NRC Branch Technical Position and guidance on expert elicitation.
ACNW	9/26-27/1996	86th ACNW Meeting	Las Vegas, Nevada	Discussion of flow and radionuclide transport at Yucca Mountain, site characterization integration through the use of performance assessment, and repository design for the viability assessment.
NWTRB	4/30-5/1/96	Full Board Meeting	Austin, Texas	Discussion of Program planning and integration of major Program activities and priorities used to define tasks and to allocate resources. The discussion included the relationship of the major Program elements and the rationale underlying those relationships, such as the waste isolation strategy and insights from performance assessment, and the rationale underlying the decisions being made regarding exploration and testing priorities. Additional discussion focused on updates on the ESF and the scientific program.

Interactions with the U.S. Nuclear Regulatory Commission and Other Organizations (continued)

Organization	Date	Type	Location	Subject/Purpose
NWTRB	7/9-10/96	Full Board Meeting	Denver, Colorado	Discussion focused on exploration and testing activities at Yucca Mountain and past and future climate and hydrology at Yucca Mountain. Specific topics discussed at the meeting related to the ESF included updates on tunnel boring machine operations and scientific investigations, lessons learned from ESF exploration to date, and the status of the waste isolation strategy and thermal testing. Topics related to climate and hydrology included the geological structure at Yucca Mountain, historical perspectives and current views on climate and hydrology, and climate modeling.

PROGRESS REPORT #15

APPENDIX E

Status of U.S. Nuclear Regulatory Commission Analysis Open Items

APPENDIX E

Status of U.S. Nuclear Regulatory Commission Site Characterization
Analysis Open Items

This appendix documents the resolution status of U.S. Nuclear Regulatory Commission (NRC) concerns as documented in the Site Characterization Analysis (SCA) (NRC, 1989). The SCA documents the NRC staff's concerns resulting from its review of the U.S. Department of Energy (DOE) Site Characterization Plan (DOE, 1988) for Yucca Mountain. The SCA consists of objections, comments, and questions. Open items are objections, comments, and questions that have not yet been resolved. The DOE tracks the status of these open items through closure by the NRC.

For each objection, comment, and question, Appendix E provides a short description of the item and its date of closure (if closed). It also briefly describes actions in progress to address the items that are still open.

Status of Site Characterization Analysis Open Items

Item ID	Item Description	Status	Action Description
Objection 1	Adequacy of Title I design control process.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this objection closed.
Objection 2	Acceptability of DOE Quality Assurance Program.	Closed 3/2/92	NRC letter lifting Objection 2. NRC considers this objection closed.
Comment 1	A systematic, iterative approach to identify and collect data during site characterization to support a license application not demonstrated to be in place.		Submit a supplemental response to the NRC. This response will be used to close Comments 10, 18, 49, and 60.
Comment 2	Performance Assessment: Confidence in performance.		Submit a supplemental response to the NRC.
Comment 3	Reliance on expert judgment to supply licensing information.		Supplemental response submitted to the NRC on 6/1/95. Awaiting NRC concurrence.
Comment 4	Rationale for the testing needs; integration of testing with design and performance assessment needs.		Develop parametric calculations to refine parameter goals. Develop plans for collecting all necessary data. Supply NRC with the information in semiannual progress reports. Submit a supplemental response to the NRC.
Comment 5	Waste Package: Interpretation of substantially complete containment.	Closed 7/11/94	NRC Evaluation of DOE response. NRC considers this comment closed.
Comment 6	Performance Assessment: Hypothesis Testing Table and alternative conceptual models.		Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 7	Use of expert judgment versus peer review.		Supplemental response submitted to the NRC on 7/12/93. Awaiting NRC concurrence.
Comment 8	Alternative Tectonic Models.		Study Plan 8.3.1.17.4.12, Rev. 1 "Tectonic Models and Synthesis" submitted to the NRC on 12/19/94.
Comment 9	Use of expert judgment during the development of Hypothesis Testing Table.		Submit a supplemental response to the NRC.
Comment 10	Assessment of significance of site hydrologic characteristics.		Resolve concerns in Comment 1. Resolution of Comment 1 will address the cross-issues for this comment.
Comment 11	No hypothesis on the thermal effects of waste emplacement in the hydrologic environments presented.		Submit a supplemental response to the NRC.
Comment 12	Porous flow in the Calico Hills unit.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 13	Surface Hydrology: Surface water gaging station locations and the natural infiltration measurements.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 14	Hydrologic properties of the tuffaceous beds of the Calico Hills nonwelded unit.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 15	Solitario Canyon horizontal borehole activity is inadequate to discriminate between the hypotheses that faults are barriers to fluid flow in non-welded tuff units or faults are conduits for liquid-water flow.	Closed 9/15/94	NRC evaluation of Study Plan 8.3.1.2.2.4. NRC considers this comment closed.
Comment 16	Characterization of the hydrologic properties of the Calico Hills unit.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 17	Multi-purpose borehole testing near the shafts.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 18	Initial hydrologic modeling studies are not supported by planned studies.		Resolve concerns in Comment 1. Resolution of Comment 1 will address cross issues for this comment.
Comment 19	Saturated Zone: Work is not adequate for saturated zone characterization.		Develop and submit plan to define sufficient testing of the saturated zone. Submit a supplemental response to the NRC.
Comment 20	Saturated Zone: Potentiometric surface will not adequately be defined.		Submit a supplemental response to the NRC.
Comment 21	Saturated Zone: technetium-199 and iodine-129 are not included to be characterized in the ground water flow and radionuclide analysis background concentrations.		Supplemental response submitted to the NRC on 1/7/93. Awaiting NRC concurrence.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 22	Saturated Zone: Hydrochemical samples.		Supplemental response submitted to the NRC on 1/7/93. Awaiting NRC concurrence.
Comment 23	Unsaturated Zone: Evaluation of radionuclide concentrations on fracture surfaces.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 24	Approaches are not sufficient for determining reliable thermodynamic properties.		Receive Study Plan from Los Alamos National Laboratory.
Comment 25	Waste Package: Rationale on additional testing on waste and interactions between and among radionuclides on sorption.		Submit Study Plan 8.3.4.2.4.1 "Characterization of Chemical and Mineralogical Changes in Post-Emplacement Environment" to NRC. Submit a supplemental response to the NRC.
Comment 26	Sorption Batch Studies.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 27	Batch Sorption Measurements.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 28	Sorption on Particulates and Colloids.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 29	Biological Sorption and Transport.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 30	Solubility Modeling.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 31	Some parameters and conditions under fracture flow are not planned and need to be determined.		Submit a supplemental response to the NRC.
Comment 32	Rock characteristics program: Geophysical integration is insufficient.		Geophysical Integration Group needs to develop a plan to implement integration. Submit a supplemental response to the NRC.
Comment 33	Engineering rock parameters are not adequately integrated to develop three-dimensional rock characteristics models.		Study Plan 8.3.1.4.3.1 "Systematic Acquisition of Site Specific Data" submitted to the NRC on 1/11/93. Study Plan 8.3.1.4.2.3 "Three-Dimensional Geologic Modeling" and supplemental response submitted to the NRC on 9/27/96. Awaiting NRC response.
Comment 34	Drilling Program: It is unclear how data from various drill holes will be used in support of various studies, how uncertainties in core retrieval and data analyses will be handled, and how the large volume of existing information will be used to plan the drilling program.		Supplemental response submitted to the NRC on 3/3/92. Awaiting NRC concurrence.
Comment 35	Adequacy of lithological, structural, and drifting activities to characterize the site.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 36	Rationale for Investigation 8.3.1.4.2 may not be accurate for the perimeter drift defining lower concentrations of faults.		Supplemental response submitted to the NRC on 6/16/94. Awaiting NRC concurrence.
Comment 37	Identification of blast fractures.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 38	Characterization of faults in the subsurface.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 39	Systematic Drilling Program: No assessment is provided to support the estimated maximum range of statistical correlation for porosity and air permeability.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 40	Systematic Drilling Program: Spacing of the 30 sample borehole pairs in a range of up to 10,000 feet may represent a lower bound for geostatistical analysis.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 41	Systematic Drilling Program: Tight clustering of sample locations USW SD-8 and USW SD-12 has not been justified.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 42	Adequacy of evaluation of escarpment retreat.	Closed 2/29/96	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 43	Adequacy of numerical goals in erosion, postclosure tectonics, and preclosure tectonics performance assessment tables.	Closed 2/17/95	NRC evaluation of the 7/23/92 DOE supplemental response provided in 2/17/95 letter from Bell to Milner. NRC considers this comment closed.
Comment 44	Waste Package: Overall goal is not consistent with substantially complete containment.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 45	Volcanic rate calculations independent of underlying volcanic-tectonic processes.		Supplemental response submitted to the NRC on 7/12/93. Awaiting NRC concurrence.
Comment 46	Postclosure Tectonics.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 47	Waste Package: Relationship of postclosure tectonics to the waste package and the engineering barrier system requirements.		Supplemental response submitted to the NRC on 6/9/93. Awaiting NRC concurrence.
Comment 48	Use of fault slip rates on the repository facilities are not conservative.		Prepare and issue topical report "Seismic Design Criteria" in accordance with the Seismic Hazards Issue Resolution Group's Issue Resolution Action Plan. Submit a supplemental response to the NRC.
Comment 49	Volcanism: Results from investigations on basaltic volcanism may fail to meet overall system performance.	Closed 9/14/94	NRC evaluation of Study Plan 8.3.1.8.1.2. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 50	Effects of faulting may be underestimated.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers the comment closed.
Comment 51	Adequacy of Geophysics program to determine deep and shallow crustal features.		Geophysical Integration group needs to develop a plan to implement integration.
Comment 52	Use of Geophysics to identify volcanic/igneous features.		Completed assessment by independent consultant of planned and potential geophysical studies that contribute to resolution of volcanism issue. Consultant's preliminary findings were submitted to the NRC on site representative. Submit a supplemental response to the NRC.
Comment 53	Adequacy of natural resource assessment; consideration of ore deposition models.		Supplemental response submitted to the NRC on 2/5/93 in Study Plan 8.3.1.9.2.1. NRC Letter 2/18/94 Holonich to Shelor partially closing Site Characterization Analysis Comment 53. Supplemental response submitted to the NRC on 10/07/94. Awaiting NRC concurrence.
Comment 54	Inconsistencies in Site Characterization Plan Chapter 8.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 55	Adequacy of geostatistical approach to geomechanical and thermal properties.		Study Plan 8.3.1.15.1.3, Rev. 1, "Rock Characteristics Program," submitted to the NRC on 6/5/95. Supplemental response submitted to the NRC 9/23/96 recommending closure of this comment.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 56	Validation of models for mechanical and thermal properties.		Submitted SP 8.3.1.15.1.5, Rev. 1 "Excavation Investigations," to NRC on 5/5/94. Submit 8.3.1.15.1.6 "In Situ Thermomechanical Properties," and 8.3.1.15.1.7, "In Situ Mechanical Properties" to the NRC. The Review of Performance Allocations for Activity 8.3.1.15 "Rock Characteristics Program" needs to be completed. Submit a supplemental response to the NRC.
Comment 57	Design verification does not consider alternative methods of excavation.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers comment closed.
Comment 58	Descriptions in the in situ design verification section do not include tests to verify design reports.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 59	Description of tectonic and igneous events do not allow for determination of actual investigations to be conducted, and sequencing of activities.		Submit a supplemental response to the NRC.
Comment 60	Performance Assessment: Adequacy of preclosure design and performance goals and characterization parameters.		Resolve concerns in Comment 1. Resolution of Comment 1 will address cross-issues of this comment.
Comment 61	Assumption that future faulting will follow previous faulting.		Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 62	The studies of faulting at the surface facilities do not indicate how DOE is proposing to use standoff distances.		Submit a supplemental response to the NRC.
Comment 63	Use of pre-existing and unavailable information for the preclosure tectonics program and the surface facilities.		Submit a supplemental response to the NRC which will describe where in the study plan and the "Test and Evaluation Plan" the concerns of the NRC are addressed.
Comment 64	Adequacy of faults study for design and performance.		Submit a supplemental response to the NRC.
Comment 65	Use of domains to define areas of faulting potential	Closed 7/31/96	NRC evaluation of DOE response. NRC considers this comment closed.
Comment 66	Release via a single event 10,000 year cumulative slip earthquake.		Complete detailed study to show the facility can conservatively withstand an event exceeding the design basis ground motion. Submit a supplemental response to the NRC.
Comment 67	Data on earthquakes having a cutoff of a magnitude 5.5 may not be sufficient to support an evaluation of the effects of site geology on surface and subsurface motion.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 68	Adequacy of treatment on detachment faulting affects.		Study Plan 8.3.1.17.4.12, Rev. 1 "Tectonic Models and Synthesis" submitted to the NRC on 12/19/94.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 69	Synthesis of data on the northwest trending faulting.		Study Plan 8.3.1.17.4.12 "Tectonic Models and Synthesis" submitted to the NRC on 12/19/94.
Comment 70	Blast control procedures less important to post-closure performance are not justified.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 71	Adequacy of technologies in assessing faulting for construction, operation, and closure.		Submit a supplemental response to the NRC.
Comment 72	Adequacy of the seal program.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 73	Performance Assessment: Adequacy of required backfill hydraulic conductivity.		Resume work on the seals program investigation. Prepare the study plan for the measurement of the hydraulic conductivity (there is no numeric designator for this study plan yet). Submit a supplemental response to the NRC.
Comment 74	Testing of Seal Components: No indication is given as to whether and when the testing to evaluate the behavior of selected sealing components under in situ test conditions will be initiated.		Prepare Study Plan 8.3.3.2.2.3 "In Situ Testing of Seal Components." Submit a supplemental response to the NRC.
Comment 75	Definition of and inconsistent use of geologic setting.	Closed 12/30/93	NRC Evaluation of DOE Responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 76	NRC reviews cannot be relied on as peer reviews.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 77	Adequacy of considerations of retrieval operations in evaluating the effects of credible accidents on radiological exposure.		Evaluate the effects of credible accidents on radiological exposures during retrieval operation of the Advanced Conceptual Design. Submit a supplemental response to the NRC.
Comment 78	10 CFR Part 20 requirements need to be considered for postclosure.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 79	Waste Package: Adequacy of waste package corrosion tests for the repository.		Complete the reviews and revisions of Study Plan 8.3.4.2.4.1 "Characterization of Chemical and Mineralogical Changes in the Post Emplacement Environment" and submit to the NRC. The Lawrence Livermore National Laboratory report, "Metal Barrier Selection and Testing," LLNL SIP CM-01, Rev. 2 was submitted to the NRC on 1/31/95. Submit a supplemental response to the NRC.
Comment 80	Performance goals consistent with interpretation and intent of substantially complete containment.	Closed 3/7/95	NRC Evaluation of the 9/20/94 supplemental response. NRC considers this item closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 81	Waste Package: Adequacy of program in stress corrosion cracking behavior of waste packages.		The metals barriers scientific investigation plan was submitted to the NRC on 1/31/95. Evaluation of the extended dry concept with drift emplacement needs to be completed which may make this concern moot. The metals barrier scientific investigation must be initiated and preliminary results released. Submit a supplemental response to the NRC.
Comment 82	Waste Package: There is an inadequate discussion on how the waste package performance may be verified at the time of license application.		Prepare Study Plan 8.3.4.2.4.4 "Engineered Barrier System Field Test" and submit to the NRC. Submit a supplemental response to the NRC.
Comment 83	The term "uniform corrosion" is misleading.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 84	Issue resolution strategy and testing package for the waste package and engineering barrier system do not take into account the full range of likely natural conditions that might affect performance of the barrier.		Consider the effect of unanticipated processes and events on the overall system in the ongoing issue resolution process. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 85	Performance Assessment: Temporal changes in the state of stress due to corrosion of the container is not accounted for.		The metals barriers scientific investigation plan to be completed. Evaluation of the extended dry concept with drift emplacement needs to be completed which may make this concern moot. The metals barrier scientific investigation must be initiated and preliminary results released. Submit a supplemental response to the NRC.
Comment 86	Waste Package: Degradation modes of copper-based alloys do not appear to agree with scientific literature.		Complete the degradation modes surveys for candidate materials and test plans for promising materials. Submit a supplemental response to the NRC.
Comment 87	Waste Package: Adequacy of effects of dissimilar metal contacts causing corrosion.		Advance the waste package design that will narrow the waste package option down to three designs. Describe the use of data from galvanic testing in the waste package design plan. Submit a supplemental response to the NRC.
Comment 88	Waste Package: Assumption of reduced uncertainties because of the unsaturated zone.		The Lawrence Livermore National Laboratory scientific investigation SIP-CM-01 (Rev. 1), "Metal Barrier Selection and Testing" was submitted to the NRC on 1/31/95.
Comment 89	Waste Package: Construction materials may change the local pH and affect the corrosion of the metal containers and the leach rates of radionuclides from the glass.		Prepare Study Plan 8.3.4.2.4.5 "Manmade Materials" and submit to the NRC. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 90	Waste Package: Consideration of varying oxygen concentrations on the corrosion of metal containers.		Provide details on how the effects of oxygen on the waste package will be considered. These details will be described in the metal barriers investigation plan. Complete evaluation of the drift emplacement alternative. This alternative would make this concern moot. Submit a supplemental response to the NRC.
Comment 91	Waste Package/Performance Assessment: Consideration of alternative canisters for carbon-14 releases.		Evaluate and describe performance of alternative waste package designs to be considered in advanced conceptual design. Review the new U.S. Environmental Protection Agency standards when they become available. Alternative waste package scenarios need to be developed. A robust design may make this concern moot. Submit a supplemental response to the NRC.
Comment 92	Disturbed Zone: Boundary definition does not include properties affected by heat generated by waste emplacement.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 93	Performance Assessment: Will the site meet the performance objective for prewaste emplacement.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 94	Performance Assessment: Assumption about features, events, processes related to the hydraulic systems in the modeling strategy.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 95	Performance Assessment: Logic used to develop and screen scenarios and its implementation appear to be deficient.		NRC evaluation of DOE response (Letter Austin to Milner; 3/28/96) NRC considers this comment open.
Comment 96	Adequacy of the use of Kd for modeling heterogeneous medium.		Study Plans 8.3.1.3.4.1 "Sorption Study" and 8.3.1.3.4.3 "Development of Sorption Models" were submitted to the NRC on 8/26/94; Study Plan 8.3.1.3.5.1 "Dissolved Species Concentration Limit" was submitted to the NRC on 9/17/93. Submit a supplemental response to the NRC.
Comment 97	Adequacy of evidence to eliminate iodine as an important radionuclide.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 98	Performance Assessment: Appropriateness of weighting Complementary Cumulative Distribution Functions by expert judgment.		Continue the development of the alternative conceptual models. Address the complementary cumulative distribution Functions through the iterative total system performance assessment (TSPA) process. Prepare and provide the NRC with documentation on the TSPA and sensitivity studies (related to schedule in Comment 9). Submit a supplemental response to the NRC.
Comment 99	Performance Assessment: Quantification of all releases.		Supplemental response submitted to the NRC on 8/4/94. Awaiting NRC concurrence.
Comment 100	Performance Assessment: Adequacy of considerations of faulting release scenarios.	Closed 2/8/93	NRC evaluation of DOE responses. The NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 101	Performance Assessment: Appropriateness of equation used to estimate the partial performance for the 4th scenario class involving release along the water pathway.	Closed 3/28/96	NRC evaluation of DOE Responses. The NRC considers this comment closed.
Comment 102	Performance Assessment: Adequacy of Ross sequences in comparison to the hydrologic flow model.		Supplemental response submitted to the NRC on 8/4/94. Awaiting NRC concurrence.
Comment 103	Performance Assessment: Ross sequences address anticipated conditions and not scenarios.	Closed 3/28/96	NRC evaluation of DOE Responses. The NRC considers this comment closed.
Comment 104	Performance Assessment: Ross sequences address spent fuel but not vitrified waste form.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 105	Performance Assessment: Rationale for elimination of scenarios.		NRC evaluation of DOE responses (Letter Austin to Milner 3/28/96) NRC considers this comment open.
Comment 106	Performance Assessment: Missing coupling term for calculation of liquid phase radionuclide transport.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 107	Performance Assessment: Awaiting time in calculation is OK but care needs to be taken in the empirical complementary cumulative distribution functions in approximating.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 108	Performance Assessment: Use of the estimated partial performance measures to screen scenarios and establish goals.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 109	Performance Assessment: Adequacy of treatment of coupling time between matrix and fracture flow in hypothesis testing tables.		Continue total system performance analysis activity that will continue to analyze the coupling times for the transfer of radionuclides between matrix and fracture flow. Submit a supplemental response to the NRC.
Comment 110	Performance Assessment: Adequacy of dealing with human intrusion in the complementary cumulative distribution function.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 111	Inconsistencies exist in the Site Characterization Plan on total system performance.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 112	Adequate discussion of state variables as constants or as random variables.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 113	Consistency of definition of complementary cumulative distribution function and the unit step function.	Closed 2/8/93	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 114	The term "independent" is used instead of "mutually exclusive."	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 115	Adequacy of expanding of complementary cumulative distribution function in terms of scenario classes.	Closed 3/28/96	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 116	Individual exposures via potable water may need to be expanded.		Issuance by the U.S. Environmental Protection Agency of a new standard (40 CFR Part 191) for individual exposure standards per the Energy Policy Act of 1992. Revise issue resolution strategy for Site Characterization Plan Issue 1.2. Prepare additional response to NRC. Submit revised issue resolution strategy and response to NRC.
Comment 117	Individual exposure rate of carbon-14 may need to consider advective and diffusive flow rates.		Submit a supplemental response to the NRC.
Comment 118	The monitoring and testing activities should include long-term in situ and long-term waste package activities.		Determine testing requirements after site characteristics have advanced far enough to define the performance program. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 119	Performance Confirmation: The information presented is insufficient to determine if the confirmation program meets the requirements of 10 CFR Part 60.		Conduct NRC-DOE interaction on the performance confirmation program. Prepare Study Plan 8.3.3.2.2.3 "In Situ Testing of Seal Components" and then submit to the NRC for acceptance. Prepare Study Plan 8.3.1.15.1.6 "In Situ Thermomechanical Properties" and submit to the NRC. Prepare Study Plan 8.3.4.2.4.4 "Engineered Barrier Field Tests" and submit to the NRC. Submit a supplemental response to the NRC.
Comment 120	Model and computer code validation studies.		Prepare and provide to the NRC the model and computer code validation strategy. Submit a supplemental response to the NRC.
Comment 121	Exploratory Shaft Facility: Adequacy of seismic design of Exploratory Shaft Facility.		Exploratory Studies Facility Design Requirements submitted on 9/9/94. Awaiting NRC concurrence.
Comment 122	Demonstration and acceptability of the dry coring method.		Supplemental response submitted to the NRC on 3/30/94. Awaiting NRC concurrence.
Comment 123	Assessment of effects of ventilation on the Exploratory Shaft Facility.	Closed 6/21/94	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 124	Potential causes for a reduction in the drainage capacity.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 125	Existing data used in the licensing process needs to be qualified.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Comment 126	Items covered by 10 CFR Part 60 (G) are incomplete.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 127	Design Acceptability Analysis.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 128	Requirements applicable to the Exploratory Shaft Facility.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 129	Design Acceptability Analysis and the Exploratory Studies Facility Design Requirements do not consider 10 CFR Part 60 requirements.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 130	Only 22 of fifty-two (52) requirements applicable to the Exploratory Shaft Facility were focused on in the Title I design. The rigor and completeness of the Design Acceptability Analysis are questioned.		Supplemental response submitted to the NRC on 3/3/92. Additional supplemental response submitted to the NRC on 9/25/96. Awaiting NRC concurrence.
Comment 131	Design Acceptability Analysis.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.
Comment 132	Design Acceptability Analysis.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this comment closed.
Comment 133	Design Acceptability Analysis.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this comment closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 1	Integration of mapping efforts.	Closed 12/30/93	NRC evaluation of DOE responses. NRC considers this question closed.
Question 2	Performance Assessment: Relation between mechanical and hydraulic apertures.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 3	Repository Design: Rationale used for selecting the total repository area is not presented.		Supplemental response submitted to the NRC on 5/17/94. Awaiting NRC concurrence.
Question 4	Adequacy of temperature logging to evaluate anomalously low heat flow.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 5	Adequacy of vertical boreholes for evaluation of faults and fractures.		Submitted supplemental response to the NRC on 6/16/94. Awaiting NRC concurrence.
Question 6	Meaning of statement in last paragraph page 8.3.1-75.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 7	Face mapping of exploratory drifts restricted to areas of anomalous conditions.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 8	Rock Properties: Level of detail and uncertainty in three-dimensional model.		Submitted Study Plan 8.3.1.4.3.1 "Systematic Acquisition of Site-Specific Subsurface Information" to the NRC for review on 1/19/93. Submit Study Plan 8.3.1.4.3.2 "Three-Dimensional Rock Characteristics Models" to the NRC for review. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 9	Systematic Drilling Program: Adequacy of sampling same sequences for rock properties.		Submitted Study Plan 8.3.1.4.3.1 "Systematic Acquisition of Site-Specific Subsurface Information" to the NRC for review on 1/19/93. Submit a supplemental response to the NRC.
Question 10	How will three-dimensional block model account for variability in the block?	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 11	Rationale to start drilling prior to approval of study plans.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 12	Rationale for exclusion of lunar crater basaltic field as natural analog.		Submitted supplemental response to the NRC on 6/9/93. Awaiting NRC concurrence.
Question 13	Basis for statements made about the migration, structural boundaries, and stage of volcanism.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 14	Natural Resources: Adequacy of evaluation of previous mining and drilling leases.	Closed 2/18/94	NRC evaluation of DOE responses. NRC considers this question closed.
Question 15	Resource exploration and mineral resource potential.	Closed 2/18/94	NRC evaluation of DOE responses. NRC considers this question closed.
Question 16	Methods for determining the impact of ground motion from underground nuclear explosions.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 17	Rock Properties: Activities to investigate effects on.	Closed 4/21/93	NRC evaluation of DOE responses. NRC considers this question closed.
Question 18	Allowable movements on joints related to rock mass strength.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 19	Side Looking Airborne Radar (SLAR).	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 20	Repository Design: Discussion of vertical or horizontal emplacement.		Supplemental response submitted to the NRC on 6/16/94. Awaiting NRC concurrence.
Question 21	Process to assure the parameters for performance goal C2 (radiation shielding of rock) is comprehensive enough and expected values realistic.		Further develop the advanced conceptual design. Submit a supplemental response to the NRC.
Question 22	Parameters related to repository construction and operation.		Supplemental response submitted to the NRC on 3/30/94. Awaiting NRC concurrence.
Question 23	Computer code verification and validation.		Submit a supplemental response to the NRC.
Question 24	Justification that the shaft liner does not provide structural support for the formation.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 25	Heterogeneous air flow characteristics for seal program.		Supplemental response submitted to the NRC on 4/13/93. Awaiting NRC concurrence.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 26	Inconsistency between tentative Design Goals and Design Performance Goals.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 27	Storage capacity at base of shaft for attaining the tentative design goals.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 28	ES-1 penetration of the Calico Hills Unit: Impacts of the current sealing program and issue resolution strategy 4.4.		Supplemental response submitted to the NRC on 3/3/92. Awaiting NRC concurrence.
Question 29	Justification that references cited present results representative of conditions at Yucca Mountain.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 30	Waste Package: Water quality as related to waste package design.		The metal barriers scientific investigation plan was submitted to the NRC on 1/31/95. Complete evaluation of the drift emplacement alternative needs. Submit a supplemental response to the NRC.
Question 31	Waste Package: Integrity of spent fuel cladding.		Supplemental response submitted to the NRC on 9/16/92. Awaiting NRC concurrence.
Question 32	Waste package: Container "similarity" for borosilicate glass waste vs. spent fuel.		Advance the waste package design and narrow the waste package options down to three designs. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 33	Waste Package: Emplacement hole drainage concerns.		Evaluate water-vapor interface, crevice corrosion, and galvanic corrosion testing in the metal barriers scientific investigation plan during advanced conceptual design. Complete evaluation of the drift emplacement alternative. This alternative would make this concern moot. Submit a supplemental response to the NRC.
Question 34	Waste Package/Performance Assessment: Meaning of undetected defective closures.		Submit a supplemental response to the NRC.
Question 35	Waste Package: Acceptance criteria for helium leak results.	Closed 3/7/95	NRC Staff evaluation of the 12/02/94 supplemental response. NRC considers this item closed.
Question 36	Waste Package: Contact of canisters with corrosive elements during shipping and handling.		Advance the waste package design and narrow options down to three designs. Submit a supplemental response which will further address the issue of eliminating corrosion elements during manufacture of the container to the NRC.
Question 37	Waste package: Basis for 10-cm of free fall for canister and contents.	Closed 3/7/95	NRC evaluation of the 11/23/94 supplemental response. NRC considers this question closed.
Question 38	What is the basis for the 1-mm thinning criterion for waste package scratching.		Submitted a supplemental response to the NRC on 7/12/93. Awaiting NRC concurrence.
Question 39	Waste Package: Defining "unusual process history" of canister.		Advance the design of the waste package. Submit a supplemental response to the NRC.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 40	Waste Package: Basis for factor of 2 on borehole liner in comparison to container material.		Study effects of water containing liner corrosion products on degradation of the container in accordance with the metal barriers scientific investigation plan. Submit a supplemental response to the NRC.
Question 41	Repository: Consideration of 10 CFR 60.132 (a) in resolution of Issue 2.4.		Conduct engineering studies to evaluate the waste throughput requirements. Submit a supplemental response to the NRC.
Question 42	Repository: Assumption of stability of vertical emplacement hole.		Advance the advanced conceptual design. Drift emplacement may make this comment moot. Submit a supplemental response to the NRC.
Question 43	Waste Package: Anticipated operational occurrences considered part of normal conditions on the preclosure design and analysis.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 44	Waste Package/Performance Assessment: Basis for assumed numbers of breached assemblies or canisters.		Provide information on failures of waste forms in multiple locations. Prepare and provide the NRC with documentation on the Total System Performance Assessment. Advance the Advanced Conceptual Design and narrow options to two candidate designs. Submit a supplemental response to the NRC.
Question 45	Waste Package: Investigation of particulate source terms, retention factors, and plate-out of waste package during accident conditions.		Supplemental response submitted to the NRC on 11/8/94. Awaiting NRC concurrence.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 46	Waste Package: Basis for stricter containment of long half-life isotopes.	Closed 7/11/94	NRC evaluation of DOE response. NRC considers this question closed.
Question 47	Waste Package: Assumption on breached waste containers.	Closed 3/7/95	NRC evaluation of the 9/20/94 supplemental response. NRC considers this question closed.
Question 48	Waste Package: Selection of peer review panel on waste package.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 49	Waste Package: Effects of low temperature oxidation on containers.		Advance the design of the waste package to three options. The metal barriers scientific investigation plan was submitted to the NRC on 1/31/95.
Question 50	Waste Package: Assumption that stress propagation results in corrosion.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 51	Design second research criteria for accepting waste from Idaho National Engineering Laboratory and Hanford.	Closed 11/8/94	NRC evaluation of DOE responses. NRC considers this question closed.
Question 52	Waste Package: Leaching properties specification will require the producer to control leaching characteristics of the glass waste.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 53	Waste Package: Specification of cooling rate of the glass waste.	Closed 3/7/95	NRC evaluation of the 10/07/94 supplemental response. NRC considers this question closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 54	Waste Package: Release rates of radionuclides from spent fuels.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 55	Exploratory Shaft Facility: Interference at the Exploratory Shaft Facility by waste storage tanks, septic field, and waste water lagoon.		Submit a supplemental response to the NRC.
Question 56	Basis for 5 cm of fault displacement in waste package environment.		Supplemental response submitted to the NRC on 5/17/94. Awaiting NRC concurrence.
Question 57	Effects of drilling multipurpose boreholes.		Supplemental response submitted to the NRC on 3/24/93. Awaiting NRC concurrence.
Question 58	Flexibility of the Exploratory Shaft Facility design to accommodate in situ testing of the waste package, if required.		Supplemental response submitted to the NRC on 1/31/94. Awaiting NRC concurrence.
Question 59	Basis for length of in situ thermal tests.		Prepare Study Plan 8.3.1.15.1.6 "In Situ Thermomechanical Properties" and submit to NRC. Submit a supplemental response to the NRC.
Question 60	Exploratory Shaft Facility: Timing of Exploratory Shaft Facility radial borehole test.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.
Question 61	Exploratory Shaft Facility: Accommodation of design changes during Exploratory Shaft Facility construction.	Closed 11/2/92	NRC letter lifting Objection 1. NRC considers this question closed.

Status of Site Characterization Analysis Open Items (continued)

Item ID	Item Description	Status	Action Description
Question 62	Repository: Basis for 500 feet of separation from Exploratory Shaft Facility and waste emplacement panel.		Submit a supplemental response to the NRC.
Question 63	Certifying Training Attendance Record reviewers were not principal investigators.	Closed 7/31/91	NRC evaluation of DOE responses. NRC considers this question closed.

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APPENDIX F

Determination of Importance Evaluations

PROGRESS REPORT #15

APPENDIX F

Determination of Importance Evaluations

This appendix lists determination of importance evaluations performed during this reporting period. Performance of a determination of importance evaluation is the mechanism established by the Project to evaluate proposed field activities with respect to their potential for adverse impact on Q-List (DOE, 1994) items or site characterization testing. Because the natural barriers are included in the Q-List, each determination of importance evaluation essentially includes both a waste isolation evaluation and a test interference evaluation for the proposed activity. Where a reasonable potential for adverse impact is identified, the evaluation establishes appropriate quality assurance (QA) controls for the activity to prevent or limit the adverse impact. These controls are then transcribed into the applicable documents for implementing the activity; for example, field work packages, design packages, specifications, and drawings.

The determination of importance evaluation process is controlled by an Implementing Line Procedure. Provision for a determination of importance evaluation is an integral part of the planning process for all site-disturbing activities, including testing activities as well as design and construction activities. Temporary, non-quality-affecting items are evaluated to the extent that their placement, construction/erection, or operation/utilization presents a potential for adverse impact on Q-List items or site characterization testing. Any proposed use of tracers, fluids, or materials is specifically required to be evaluated. The determination of importance department receives requests for evaluations of site-disturbing activities from all Project participants.

The determination of importance procedure provides for flexibility in evaluating site impacts through the use of category definitions. Category I evaluations are for activities that would not reasonably impact Q-List items or site characterization testing. Category II evaluations are for activities where the potential impacts are encompassed by existing evaluations such that no new QA controls are warranted. Category III evaluations are used for activities that present a potential for adverse impact, but have not been previously evaluated. Category III determination of importance evaluations establish new QA controls for those activities as required.

The following determination of importance evaluations and revisions were produced during this reporting period.

Exploratory Studies Facility (ESF) Determination of Importance Evaluations

- Category II determination of importance for Exploratory Studies Facility (ESF) Ventilation System Testing Using Sulfur Hexafluoride, BABFAD000-01717-2200-00001 Rev 00: this determination of importance was prepared on an exigent basis to support resolution of the airborne dust concern in the tunnel. (The testing was designed to facilitate the determination of leakage rates in the subsurface ESF ventilation duct and consequent system recirculation percentages.) The determination of importance

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concluded that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.

- Category II determination of importance for ESF Moisture Studies, BAB000000-01717-2200-00151 Rev 00: this determination of importance was prepared to support moisture testing activities conducted in the Subsurface ESF tunnel and alcoves. The objective of the testing is to refine understanding of the moisture conditions in the subsurface ESF excavated areas and adjoining rock matrix. The determination of importance concluded that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) contains adequate Quality Assurance (QA) controls to limit any potential for adverse test interference or waste isolation impacts.
- Category II determination of importance for ESF Ground Support for the South Portal Boxcut, BAB000000-01717-2200-00153 Rev 00: this determination of importance encompassed the proposed activities associated with the installation of ground support (i.e., rockbolts, shotcrete, etc.) to stabilize the headwall and sidewalls of the South Portal Boxcut. The determination of importance concluded that the existing Category III determination of importances for the Surface ESF (DI No. BAB000000-01717-2200-00106 Rev 01) and the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05), in consideration of the controls applied in the QA Classification Analysis of Ground Support Systems (DI No. BABEE0000-01717-2200-00001 Rev 04), contain adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.
- Category II determination of importance for ESF Hydraulic Fracture Testing, BABEAF000-01717-2200-00004 Rev 00: this determination of importance was prepared to support hydraulic fracture testing activities to be conducted in the Topopah Spring (TS) Main Drift Thermal Testing Facility. The objective of the testing is to produce and collect in situ stress data to support the characterization of the Thermal Testing Facility area for performance assessment. The determination of importance (which at this writing is in review) is expected to conclude that one additional site-specific QA control is warranted for clarification of existing requirements as applied to this specific activity, and that the activity is otherwise bounded by the conclusions contained in the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05). The determination of importance further concludes that the site-specific control contained in this determination of importance coupled with the requirements contained in the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) are adequate to limit any potential for adverse test interference or waste isolation impacts.

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- Category II determination of importance for the Design and Construction of the ESF Southern Ghost Dance Fault Alcove, BABEAF000-01717-2200-00005 Rev 00: this determination of importance was prepared to support the excavation and construction activities associated with the Southern Ghost Dance Fault Alcove, located on the Main Drift of the TS Loop. The determination of importance (which at this writing is in review) is expected to conclude that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.
- Revision to the Category II determination of importance for the Design and Construction of the Topopah Spring (TS) Main Drift Thermal Testing Facility (BABEAF000-01717-2200-00002 Rev 01): this revision incorporated the proposed design and construction activities for the Connecting-Drift, Data Acquisition System Niche, Plate Loading Niche, and Turn-Around Bay within the Thermal Testing Facility. The determination of importance concluded that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.
- Revision of the Category III determination of importance for the Surface Exploratory Studies Facility, BAB000000-01717-2200-00106 Rev 01: this determination of importance revision evaluated additional construction, operation, maintenance and reclamation activities associated with the Surface ESF (not included in the previous design), Pre-Splitting Blasting of the Headwall/Boxcut for the South Portal and Pad, Environmental Reclamation, Meteorologic and Radiological Monitoring, and the South Portal Pad Site Grounding and Lightning Protection Systems.
- Determination of importance for Hydrochemistry Testing, Radial Borehole Tests, and Hydrologic Properties of Major Faults Encountered in the ESF, BAB000000-01717-2200-00146 Revision 02: this determination of importance was revised to include the evaluation of planned testing activities to be performed in the Northern and Southern Ghost Dance Fault Alcoves. The determination of importance concluded that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.
- Revision to Category II determination of importance for Exploratory Studies Facility (ESF) Ventilation System Testing Using Sulfur Hexafluoride, BABFAD000-01717-2200-00001 Rev 00: this determination of importance was revised to support additional ventilation testing required for resolution of the airborne dust concern in the tunnel. (The testing was designed to facilitate the determination of leakage rates in the subsurface ESF ventilation duct and consequent system recirculation percentages.) The determination of importance concluded that the existing Category III determination of importance for the Subsurface ESF (DI No. BAB000000-01717-2200-00005 Rev 05)

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contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.

Surface-Based Testing Determination of Importances

- Category I determination of importance for Installation and Operation of Digital Seismic Stations, BAAAD0000-01717-2200-00011 Rev 00: this determination of importance addresses the installation and operation of a network of digital seismic stations to be used for monitoring regional seismic activity. Because the location of the stations is physically remote to the potential repository location, no impacts to waste isolation or site characterization activities are anticipated.
- Revision to the Category II determination of importance for C-Hole Complex Testing, BAAAD0000-01717-2200-00008 Rev 03: this determination of importance revision updated the controls that had been established for surface water application at the C-Hole Complex, and updated the references for the determination of importance. The determination of importance concluded that the existing Category III determination of importance for the Surface ESF (DI No. BAB000000-01717-2200-00106 Rev 01) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.
- Category I determination of importance for Placement of Temporary Remote Seismic Instrumentation on Pads for Surface Boreholes USW SD-7a and UZ-14, and the Large Block Test, BAA000000-01717-2200-00102 Rev 00: this determination of importance addresses the installation and operation of sets of three remote seismic monitoring stations located in the disturbed area of the Large Block Test and on the drill pads for SD-7 and UZ-14. The stations are to be located on previously-disturbed ground and the associated activities are limited in scope and duration such that additional disturbance is negligible; no impacts to waste isolation or site characterization activities are anticipated.
- Category II determination of importance for Surface-Based Testing Reclamation Activities, BAA000000-01717-2200-00103 Rev 00: this determination of importance addresses the backfilling of test pits/trenches and environmental activities associate with reclamation of various Surface-Based Testing sites utilized for Yucca Mountain Site Characterization Program. The determination of importance (which at this writing is in review) is expected to conclude that the existing Category III determination of importance for the Surface ESF (DI No. BAB000000-01717-2200-00106 Rev 01) contains adequate QA controls to limit any potential for adverse test interference or waste isolation impacts.

PROGRESS REPORT #15

APPENDIX G

Study Plan Status

PROGRESS REPORT #15

APPENDIX G

Study Plan Status

This appendix shows the completion and review status of each study plan. Study plans are the means chosen to describe test plans, the methods to be used, the results expected, and how the results will be applied. They are the control mechanisms for the investigations that make up the site characterization program.

Information presented in Appendix G includes the study plan number and title, as well as the following dates:

- date of submittal to the Yucca Mountain Site Characterization Office
- date of approval by the Yucca Mountain Site Characterization Office
- date of completion of U.S. Nuclear Regulatory Commission initial review with no objections
- date of receipt of comments from the State of Nevada

Study Plan Status

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.2.1.1	Characterization of the Meteorology for Regional Hydrology	6/26/90	3/13/91	10/21/91	12/10/91
8.3.1.2.1.2	Characterization of Runoff and Streamflow	3/27/89	8/21/90	5/14/91	4/12/91
8.3.1.2.1.3	Characterization of the Regional Ground-Water Flow System	3/1/90	1/18/91	10/4/91	3/19/93
8.3.1.2.1.4	Regional Hydrologic System Synthesis and Modeling	6/6/90	12/18/91	5/6/92	1/29/93
8.3.1.2.2.1	Characterization of Unsaturated-Zone Infiltration	3/9/90	1/18/91	5/31/91	
8.3.1.2.2.2, R0	Water Movement Test	9/23/87	11/9/89	4/8/93	
8.3.1.2.2.2, R1	Water Movement Test	10/17/91	2/10/93	4/8/93	
8.3.1.2.2.3	Characterization of Percolation in the Unsaturated Zone—Surface-Based Study	8/12/88	4/8/91	3/26/92	
8.3.1.2.2.4	Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility (.4, .5, .7, .8, .9)	9/9/87	1/9/89	3/5/93	
8.3.1.2.2.4, R1	Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility (.4, .5, .7, .8)	12/4/92	1/14/93	3/5/93	
8.3.1.2.2.4, R2	Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility (.10)	3/16/93	6/2/94	9/15/94	
8.3.1.2.2.4, R3	Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility (.1, .2)	4/29/94	5/15/96		

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.2.2.5	Diffusion Tests in the Exploratory Studies Facility	11/1/88	4/22/92	1/19/93	11/1/93
8.3.1.2.2.5, R1	Diffusion Tests in the Exploratory Studies Facility	5/19/95	Waiting on Principal Investigator's revisions		
8.3.1.2.2.6	Characterization of Gaseous-Phase Movement in the Unsaturated Zone	6/12/89	6/11/91	10/7/91	5/1/92
8.3.1.2.2.6, R1	Characterization of Gaseous-Phase Movement in the Unsaturated Zone	4/6/93	9/30/93		
8.3.1.2.2.7	Hydrochemical Characterization of the Unsaturated Zone	10/24/88	9/18/90	5/1/92	12/28/92
8.3.1.2.2.7, R1	Hydrochemical Characterization of the Unsaturated Zone	12/1/92	9/9/93	1/26/94	
8.3.1.2.2.8	Fluid Flow in Unsaturated, Fractured Rock	9/7/90	8/12/92	1/28/93	
8.3.1.2.2.8, R1	Fluid Flow in Unsaturated, Fractured Rock	12/1/92	12/17/93	8/23/94	
8.3.1.2.2.9	Site Unsaturated-Zone Modeling and Synthesis	1/25/91	7/1/93	11/8/93	
8.3.1.2.3.1.1-6	Characterization of the Site Saturated-Zone Ground-Water Flow System	5/31/89	2/13/91	12/6/91	
8.3.1.2.3.1.7	Characterization of the Site Saturated-Zone Ground-Water Flow System	2/8/88	2/22/90	12/6/91	

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.2.3.2	Characterization of the Saturated-Zone Hydrochemistry	3/28/90	4/22/92	1/4/93	
8.3.1.2.3.3	Saturated-Zone Hydrologic System Synthesis and Modeling	9/4/90	1/14/93	6/16/93	
8.3.1.3.1.1	Ground-Water Chemistry Model	3/15/91	5/4/94		
8.3.1.3.2.1	Mineralogy, Petrology, and Chemistry of Transport Pathway	1/22/88	6/13/89	8/20/90	12/28/92
8.3.1.3.2.2	History of Mineralogical and Geochemical Alteration of Yucca Mountain	3/28/88	12/18/91	4/27/92	1/24/94
8.3.1.3.3.1	Natural Analog of Hydrothermal Systems in Tuff	No study plan to be developed, overlaps planned activities in Study Plans 8.3.4.2.4.1 and 8.3.1.20.1.1			
8.3.1.3.3.2	Kinetics and Thermodynamics of Mineral Evolution	3/25/94	Still in review		
8.3.1.3.3.3	Conceptual Model of Mineral Evolution	Combined with Study Plan 8.3.1.3.3.2			
8.3.1.3.4.1	Batch Sorption Studies	10/28/92	8/4/94		
8.3.1.3.4.2	Biological Sorption and Transport	12/12/88	11/25/92	3/25/93	
8.3.1.3.4.3	Development of Sorption Models	Combined with Study Plan 8.3.1.3.4.1			

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.3.5.1/2	Dissolved Species Concentration Limits and Colloid Behavior (8.3.1.3.5.1 and 8.3.1.3.5.2 have been combined)	9/7/90	9/9/93		
8.3.1.3.6.1	Dynamic Transport Column Experiments	3/10/93	9/30/96		
8.3.1.3.6.2	Diffusion	7/24/89	8/6/93	1/19/94	
8.3.1.3.7.1	Retardation Sensitivity Analysis	12/14/88	8/11/92	1/19/93	
8.3.1.3.7.2	Demonstration of Applicability of Laboratory Data to Repository Transport Calculations	Out year – under development			
8.3.1.3.8.1	Gaseous Radionuclide Transport Calculations and Measurements	No study plan to be developed Work Scope covered under Study Plan 8.3.1.2.2.6 and Activity 8.3.1.3.7.1.3.			
8.3.1.4.2.1	Characterization of the Vertical and Lateral Distribution of Stratigraphic Units Within the Site Area	4/12/90	6/9/92	12/14/92	
8.3.1.4.2.2	Characterization of the Structural Features Within the Site Area	9/4/87	2/3/89	2/8/93	
8.3.1.4.2.2, R1	Characterization of the Structural Features Within the Site Area (.3, .5)	2/27/90	4/22/92	2/8/93	

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.4.2.2, R2	Characterization of the Structural Features Within the Site Area (.3, .5)	11/18/92	12/22/92	2/8/93	2/11/94
8.3.1.4.2.3	Three-Dimensional Geologic Model	2/13/95	9/19/96		
8.3.1.4.3.1	Systematic Acquisition of Site-Specific Subsurface Information	3/27/90	12/8/92	7/19/93	
8.3.1.4.3.2	Three-Dimensional Rock Characteristics Models	5/4/94	9/18/95		
8.3.1.5.1.1	Characterization of Modern Regional Climate	6/24/93	7/25/94		
8.3.1.5.1.2	Paleoclimate Study: Lake, Playa, and Marsh Deposits	10/25/90	10/31/91	4/27/92	1/24/94
8.3.1.5.1.3	Climatic Implications of Terrestrial Paleocology	2/11/91	1/17/92	8/27/92	1/24/94
8.3.1.5.1.4	Analysis of the Paleoenvironmental History of the Yucca Mountain Region	3/30/90	5/29/91	12/06/91	1/11/93
8.3.1.5.1.5	Paleoclimate-Paleoenvironmental Synthesis	2/2/95	3/15/96		
8.3.1.5.1.6	Characterization of the Future Regional Climate and Environments	12/29/93	6/15/94	10/18/94	
8.3.1.5.2.1	Characterization of the Quaternary Regional Hydrology (.3, .4, .5)	1/26/88	6/8/89	11/24/89	4/9/91
8.3.1.5.2.1, R2	Characterization of the Quaternary Regional Hydrology (.1)	9/25/90	11/10/92	6/24/93	11/1/93
8.3.1.5.2.2	Characterization of Future Regional Hydrology Due to Climate Changes	1/16/91	11/10/92	4/5/93	11/1/93

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.6.1.1	Distribution and Characteristics of Present and Past Erosion	No study plans to be developed, superseded by the Erosion Topical Report			
8.3.1.6.2.1	Influence of Future Climatic Conditions on Locations and Rates of Erosion				
8.3.1.6.3.1	Evaluation of the Effects of Future Tectonic Activity on Erosion at Yucca Mountain				
8.3.1.6.4.1	Development of a Topical Report on the Effects of Erosion				
8.3.1.8.1.1	Probability of Magmatic Disruption of the Repository	3/29/89	9/19/90	10/5/91	8/8/91
8.3.1.8.1.1, R3	Probability of Magmatic Disruption of the Repository	11/20/95	5/15/96		
8.3.1.8.1.2	Physical Processes of Magmatism and Effects on the Repository	10/21/92	9/21/93	9/14/94	
8.3.1.8.2.1	Analysis of Waste Package Rupture Due to Tectonic Processes and Events	12/15/89	11/16/92	11/19/93	
8.3.1.8.2.1, R1	Tectonic Effects: Evaluations of Changes in the Natural and Engineered Barrier Systems Resulting from Tectonic Processes and Events	2/18/94	5/9/96		

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO^a	Approved by YMSCO^b	Reviewed by NRC^c	Reviewed by NV^d
8.3.1.8.3.1	Analysis of the Effects of Tectonic Processes and Events on Average Percolation Flux Rates Over the Repository	These studies have been combined into 8.3.1.8.2.1 R1			
8.3.1.8.3.2	Analysis of the Effects of Tectonic Processes and Events on Changes in Water-Table Elevation				
8.3.1.8.3.3	Analysis of the Effects of Tectonic Processes and Events on Local Fracture Permeability and Effective Porosity				
8.3.1.8.4.1	Analysis of the Effects of Tectonic Processes and Events on Rock Geochemical Properties				
8.3.1.8.5.1	Characterization of Volcanic Features	12/14/88	4/18/90	8/20/90	2/21/91
8.3.1.8.5.2	Characterization of Igneous Intrusive Features	10/13/92	3/7/94	8/22/94	
8.3.1.8.5.3	Investigation of Folds in Miocene and Younger Rocks of the Region	No study plan to be developed			
8.3.1.9.1.1	An Evaluation of Natural Processes that Could Affect the Long-Term Survivability of the Surface Marker System at Yucca Mountain				
8.3.1.9.2.1	Natural Resource Assessment of Yucca Mountain, Nye County, Nevada	7/13/90	11/6/92	3/16/93	2/11/94
8.3.1.9.2.2	Water Resource Assessment of Yucca Mountain, Nevada	10/6/89	8/26/91	5/4/92	12/28/92

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.9.3.1	Evaluation of Data Needed to Support an Assessment of the Likelihood of Future Inadvertent Human Intrusion at Yucca Mountain as a Result of Exploration and/or Extraction of Natural Resources	No study plans to be developed			
8.3.1.9.3.2	An Evaluation of the Potential Effects of Exploration for, or Extraction of, Natural Resources on the Hydrologic Characteristics at Yucca Mountain				
8.3.1.12.2.1	Meteorological Data Collection at the Yucca Mountain Site	9/28/90	3/20/91	11/12/91	12/2/91
8.3.1.12.2.1, R1	Meteorological Data Collection at the Yucca Mountain Site	3/31/92	8/9/93		
8.3.1.12.2.1, R2	Meteorological Data Collection at the Yucca Mountain Site	5/20/96	7/1/96		
8.3.1.14.2	Studies to Provide Soil/Rock Properties of Potential Locations of Surface/Subsurface Facilities	7/15/91	10/01/91	1/24/92	4/6/92
8.3.1.15.1.1	Laboratory Thermal Properties	3/17/88	10/21/90	8/22/94	
8.3.1.15.1.1, R1	Laboratory Thermal Properties	11/3/92	8/27/93	8/22/94	
8.3.1.15.1.2	Laboratory Thermal Expansion Testing	12/1/88	8/21/90	8/22/94	
8.3.1.15.1.2, R1	Laboratory Thermal Expansion Testing	11/3/92	8/27/93	8/22/94	
8.3.1.15.1.3	Laboratory Determination of Mechanical Properties of Intact Rock	2/8/88	5/21/91	Deferred	

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.15.1.3, R1	Laboratory Determination of Mechanical Properties of Intact Rock	7/19/93	5/15/95		
8.3.1.15.1.4	Laboratory Determination of the Mechanical Properties of Fractures	10/23/91	12/14/94		
8.3.1.15.1.5	Excavation Investigations	3/26/87	1/09/89	8/19/94	
8.3.1.15.1.5, R1	Excavation Investigations	3/18/93	4/22/94	8/19/94	
8.3.1.15.1.6	In Situ Thermomechanical Properties	1/5/96	5/9/96		
8.3.1.15.1.7	In Situ Mechanical Properties	2/1/96	7/19/96		
8.3.1.15.1.8	In Situ Design Verification	3/20/90	2/3/93	4/15/93	11/1/93
8.3.1.15.2.1	Characterization of the Site Ambient Stress Conditions(.2)	9/22/87	1/11/89	Deferred	
8.3.1.15.2.1, R.1	Characterization of the Site Ambient Stress Conditions(.1)				
8.3.1.15.2.2	Characterization of the Site Ambient Thermal Conditions	10/13/92	6/23/94		
8.3.1.16.1.1	Characterization of Flood Potential of the Yucca Mountain Site	3/30/89	9/17/90	5/8/91	1/22/91
8.3.1.16.2.1	Location of Adequate Water Supply for Construction, Operation, Closure, and Decommissioning of a Mined Geologic Disposal System at Yucca Mountain, Nevada	No study plan to be developed			
8.3.1.16.3.1	Determination of the Preclosure Hydrologic Conditions of the Unsaturated Zone at Yucca Mountain, Nevada	No study plan to be developed			
8.3.1.17.1.1	Potential for Ash Fall at the Site	No study plan to be developed			

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.17.2.1	Faulting Potential at the Repository	No study plan to be developed, combined with Study Plan 8.3.1.17.3.6.			
8.3.1.17.3.1	Relevant Earthquake Sources	8/1/90	12/18/91	5/18/92	1/13/93
8.3.1.17.3.1, R1	Relevant Earthquake Sources	2/18/94	5/15/96		
8.3.1.17.3.2	Underground Nuclear Explosion Sources	All activities rely on available data and are completed.			
8.3.1.17.3.3.1	Ground Motion from Regional Earthquakes	4/21/94	4/24/95		
8.3.1.17.3.3.2	Ground Motion from Underground Nuclear Explosions	2/2/94	9/6/94	12/22/94	
8.3.1.17.3.4	Effects of Local Site Geology on Surface and Subsurface Motions	7/6/90	11/14/91	6/8/92	1/11/93
8.3.1.17.3.5	Ground Motion at the Site from Controlling Seismic Events	10/4/90	7/9/93	11/2/93	
8.3.1.17.3.6	Probabilistic Seismic Hazards Analyses	10/17/94	4/12/95		
8.3.1.17.4.1	Historical and Current Seismicity	10/17/89	9/17/90	5/14/91	11/1/93
8.3.1.17.4.1, R1	Historical and Current Seismicity	11/16/93	11/9/94	2/17/95	
8.3.1.17.4.2	Location and Recency of Faulting Near the Prospective Surface Facilities	12/6/88	5/22/89	11/24/89	5/29/90
8.3.1.17.4.3	Quaternary Faulting Within 100 km of Yucca Mountain, Including the Walker Lane	3/25/92	1/21/93	9/2/93	3/3/94

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.1.17.4.4	Quaternary Faulting Proximal to the Site Within Northeast-Trending Fault Zones	8/3/92	3/18/93	9/2/93	
8.3.1.17.4.5	Detachment Faults at or Proximal to Yucca Mountain	5/1/90	7/20/92	2/1/93	1/24/94
8.3.1.17.4.6	Quaternary Faulting Within the Site Area	10/14/88	1/23/91	10/3/91	1/13/93
8.3.1.17.4.7	Subsurface Geometry and Concealed Extensions of Quaternary Faults at Yucca Mountain	No study plan to be developed, scope transferred to Study Plans 8.3.1.4.2.1 and 8.3.1.17.3.6			
8.3.1.17.4.8	Stress Field Within and Proximal to the Site Area	Canceled. Scope transferred to Study Plan 8.3.1.17.4.12			
8.3.1.17.4.9	Tectonic Geomorphology of the Yucca Mountain Region	No study plan to be developed, scope transferred to Study Plans 8.3.1.5.1.4, 8.3.1.17.4.3, and 8.3.1.17.4.2			
8.3.1.17.4.10	Geodetic Leveling	3/30/90	1/18/91	10/4/91	2/1/93
8.3.1.17.4.11	Characterization of Regional Lateral Crustal Movement	No study plan to be developed, all activities were transferred to Study Plan 8.3.1.17.4.10			
8.3.1.17.4.12	Tectonic Models and Synthesis	4/30/93	11/18/94	2/6/95	
8.3.1.17.4.12, R1	Tectonic Models and Synthesis	4/13/95	6/13/95		
8.3.1.20.1.1	Characterization of the Altered Zone	1/30/95			
8.3.3.2.2.1	Seal Material Properties Development	2/2/96	8/9/96		
8.3.3.2.2.3	In Situ Testing of Seal Components	9/16/94	7/19/96		

Study Plan Status (continued)

Study Plan Number	Study Plan Title	Submitted to YMSCO ^a	Approved by YMSCO ^b	Reviewed by NRC ^c	Reviewed by NV ^d
8.3.4.2.4.1	Characterization of the Chemical and Mineral Changes in the Postemplacement Environment	8/8/94			
8.3.4.2.4.2	Hydrological Properties of Waste Package Environment	12/20/93	2/27/95		
8.3.4.2.4.2, R1	Hydrological Properties of Waste Package Environment	2/28/95	9/20/96		
8.3.4.2.4.3	Characterization of the Geomechanical Attributes for the Waste Package Environment	6/28/89	12/11/92	4/21/93	
8.3.4.2.4.4	Engineered Barrier System Field Tests	7/9/93	10/17/95		
8.3.4.2.4.5	Effects of Man-Made Materials on Water Chemistry	4/28/94			

^aSubmitted to Yucca Mountain Site Characterization Office (YMSCO) and under review.

^bCompleted YMSCO review.

^cCompleted U.S. Nuclear Regulatory Commission (NRC) initial review with no objections.

^dReceived comments from State of Nevada.

^eR0, R1, etc., indicate revision number.

APPENDIX H

Site Characterization Program Baseline History

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Site Characterization Program Baseline History

This appendix discusses revisions that have been made to the Site Characterization Program Baseline. The baseline document provides the Program baseline against which changes to the plans for characterizing the Yucca Mountain site are documented. The baseline document also provides the objectives of each Site Characterization Plan study and information on test controls and testing constraints applicable to the Exploratory Studies Facility.

The following table shows the revision number of each of the 13 revisions that have been made to the Baseline and the date the revision was issued. The table also describes the scope and nature of each revision.

Site Characterization Program Baseline History

Revision	Issued	Revisions
0	2/22/91	Initial Issue
1	4/5/91	Updated information related to the Exploratory Studies Facility (ESF). Incorporated changes to program planning resulting from the "Exploratory Studies Facility Alternatives Study: Final Report."
2	10/2/91	Revised plans for testing in Site Characterization Plan Section 8.3.1.14. Consolidated all the expected studies under Investigation 8.3.1.14 into one Study Plan (8.3.1.14.2).
3	2/7/92	Changes to the objectives of Activities 1 and 4 in Study Plan 8.3.1.2.1.4 and Activity 4 in Study Plan 8.3.1.2.3.2. Added three drillholes to Study Plan 8.3.1.2.3.1. Deleted requirement for tagging surface dust suppression water with chemical tracer.
4	3/13/92	Incorporated changes in the objectives of Activities 1 and 3 in Study Plan 8.3.1.2.3.2.
5	7/15/92	Corrected references to integration of geophysical activities.
6	7/15/92	Updated Section 8.4 to be consistent with current Exploratory Studies Facility concept.
7	7/15/92	Deleted Activity 8.3.1.4.2.1.6 to eliminate redundancy.
8	9/24/92	Reorganized waste package near-field environment program.
9	10/2/92	Changed scope of the Site Characterization Program Baseline to delete activity descriptions that are controlled in the study plans; placed parameter tables in separate controlled document; removed hypothesis testing tables and analyses supporting test control from the Site Characterization Program Baseline. Changes made to Activities 8.3.1.2.2.4.6, 8.3.1.5.2.1.2, 8.3.1.5.2.2.1, 8.3.1.5.2.2.2, 8.3.1.5.2.2.3; changes made to Studies 8.3.1.3.7.2, 8.3.1.8.1.1, 8.3.1.8.1.2, 1.10.4.3; and changes made to Investigation 8.3.1.7.1.
10	1/14/93	Documented changes made to Study 8.3.1.2.2.4; Activities 8.3.1.8.5.2.2, 8.3.1.15.2.2, 8.3.1.17.4.3.2, 8.3.1.17.4.4.3; and Section 8.3.5.13.

Site Characterization Program Baseline History (continued)

Revision	Issued	Revisions
11	8/3/94	Combined studies 8.3.1.8.2.1, 8.3.1.8.3.1, 8.3.1.8.3.2, 8.3.1.8.3.3, 8.3.1.8.4.1 within the postclosure tectonics program into one study (8.3.1.8.2.1, Revision 1). Activity 8.3.1.8.5.2.1 was deleted because data was too ambiguous and too general to be useful. Changed Activity 8.3.1.17.3.1.
12	1/20/95	Revision to Studies 8.3.1.5.1.6 and 8.3.1.15.1.1, editorial changes to Section 8.4 that responded to comments from the U.S. Nuclear Regulatory Commission. Incorporation of revised ESF/Repository interface drawings.
13	3/30/95	Removed the test objectives that were duplicated in the Site Design and Test Requirements Document and updated the design summary to reflect current terminology.

PROGRESS REPORT #15

APPENDIX I

Tables of Technical Computer Codes

PROGRESS REPORT #15

APPENDIX I

Tables of Technical Computer Codes

This appendix lists computer codes that have been used, are being used, or could be used for design analysis, process control, scientific investigation, preclosure and postclosure performance assessments, and other technical activities.

Table I-1 lists the computer code names, including currently used or the most recent versions, a brief statement of the processes being modeled, past, current or potential applications in the Project, and references for documentation required for the approval of the computer code in accordance with the Quality Assurance Requirements and Description (DOE, 1995d). References for applications of the computer codes are not listed. Computer codes that currently meet the requirements of the Quality Assurance Requirements and Description are marked with an asterisk (*).

Table I-2 lists sections of Progress Report #15 where activities are described that identify the computer codes listed in Table I-1. To establish a one-to-one correspondence between these two tables, all computer codes listed in Table I-1 are also listed in Table I-2. Some report sections may not have identified the specific computer codes, however, that were used for the activities described.

In both tables, the names of newly listed computer codes, compared to Tables I-1 and I-2 in Progress Report #14, are in bold type. No computer codes were deleted since Progress Report #14.

Only brief descriptions and captions are given for each computer code in Tables I-1 and I-2. Although this may give the appearance that some computer codes have the same capabilities, each computer code has unique capabilities that are needed for specific purposes. The distinctive capabilities of each computer code are evident from the references listed in Table I-1 and from the applications summarized in the Progress Report sections identified in Table I-2.

The appendix does not list computer software for support functions, such as operating systems, administrative and management software, system utilities, compilers and their associated libraries, word processors, spreadsheet programs, data base managers, graphing and visual display systems, statistical analysis tools, and software that is acquired or developed as an integral part of measuring and test equipment.

Documents cited in this appendix are included in the consolidated reference list for this progress report (Appendix L).

Table I-1. Analytical Techniques

Computer codes added since Progress Report #14 are shown in bold type. No computer codes were deleted.

* = one or more versions approved for work subject to the Quality Assurance Requirements and Description

See end of table for list of abbreviations and acronyms.

Name	Process	YMP Applications	Status
3DEC* Vs. 1.5* Sep 94	Three-dimensional analysis of underground opening stability and ground motion for jointed rock masses; distinct element method	ESF and repository excavation stability analyses	User's manual (Itasca, 1994a), vs. 1.5 qualification (CRWMS M&O, 1994c); maintained by Itasca Consulting Group, Inc.
ABAQUS Vs. N/A 1982	Soil and rock mechanics analysis	Geomechanical behavior of large-block test and ESF drift-scale test	Example problems manual (Hibbitt, 1982); maintained by Hibbitt, Karlsson and Sorenson, Inc.
ANSYS* Vs. 5.0* May 93 Vs. 5.0A May 94 Vs. 5.1 Sep 94 Vs. 5.1HP* Jul 95 Vs. 5.2 Aug 95 Vs. 5.3 1996 Vs. 5.4 1996	Multi-dimensional thermal-mechanical analysis of stress, strain, and heat conduction and radiation in solids; includes design optimization; finite element method	Thermal-mechanical analyses in support of waste package development, including the multi-purpose canister	Vs. 5.0 qualification (CRWMS M&O, 1993e), vs. 5.0A qualification (CRWMS M&O, 1994d), vs. 5.1 user's manual (ANSYS, 1994a), vs. 5.1 verification (ANSYS, 1994b), vs. 5.1HP qualification (CRWMS M&O, 1995i); newer user's manuals on CD-ROM; maintained by ANSYS, Inc.
AREST Vs. 1.0 Nov 93	Radionuclide release from waste package and engineered barrier system	Engineered barrier system performance analysis in support of total system performance assessments	Theory (Liebetrau et al., 1987; Engel and McGrail, 1993), user's manual (Buxbaum and Engel, 1991); software requirements Engel et al., 1993); maintained at Pacific Northwest National Laboratory; see also AREST-CT
AREST-CT working version 1995	Coupled reactive chemical transport, radionuclide release, and effects of near-field chemistry on radionuclide transport	Engineered barrier system performance analysis in support of total system performance assessments	In development; development aspects (Engel et al., 1994; 1995, in prep.); maintained by CRWMS M&O; see also AREST

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
A-TOUGH Vs. N/A 1993	Version of V-TOUGH with atmospheric interaction	Simulation of moisture removal from the repository by ventilation	User's manual (Multimedia, 1993); maintained by Multimedia Environmental Technology, Inc.
CLIMATE working version 1996	Heat and mass transport within underground excavations, including water vapor and air ventilation	Analysis of ESF and repository drift ventilation	Development aspects (Danko et al., 1995, 1996)
CLIMSIM Vs. 2.0 1986	Climatic conditions in underground working areas considering heat sources, age, and wetness of airways	Analysis of climatic working conditions in ESF and repository drifts	User's manual (Mine Ventilation Services, 1986); maintained by Mine Ventilation Services, Inc.
COYOTE Vs. II 1994	Multi-dimensional nonlinear heat conduction and related general diffusion processes in solids	Analyses of rock temperatures surrounding the potential repository	Documentation (Gartling, 1982; Gartling and Hogan, 1994); maintained at Sandia National Laboratories
DIPS* Vs. 3.1* Jan 95 Vs. 4.0 1996	Plotting, analysis, and presentation of geologic structure using spherical projection techniques	Analysis of ESF fracture data (input to UNWEDGE)	User's manual (Diederichs and Hoek, 1996), vs. 3.1 qualification (CRWMS M&O, 1995j); maintained at University of Toronto
DORT-2D TORT-3D Vs. 2.12.14 Jan 95	Two- and three-dimensional discrete ordinates neutron and photon transport	Calculations of radiation doses in vicinity of waste packages	User's manual (ORNL, 1995a); maintained at Oak Ridge National Laboratory
Earthvision Vs. 3.0 1995 Vs. 3.1 Nov 96	Three-dimensional geologic modeling	Basis of geologic framework model for Yucca Mountain	Vs. 3.0 user's manual (Dynamic Graphics, 1995), vs. 3.1 user's manual (CRWMS M&O, in prep.[d]); maintained by Dynamic Graphics, Inc.
ELFPOINT working version 1992	Rock deformation resulting from shear and tensile faulting	Support of seismic ground-water pumping analysis to compute seismically induced elastic rock deformations	Theory (Okada, 1992)

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
EQ3/6* Vs. 7.2a* Aug 94 Vs. 7.2b Aug 95	Speciation and solubility in aqueous solutions and geochemical reaction path/mass transfer	Analyses of ground-water chemistry data, calculations of solubility limits, and determination if certain reactions are in equilibrium or disequilibrium states	Theory and user's manual (Daveler and Wolery, 1992; Wolery, 1992a and b; Wolery and Daveler, 1992); maintained at Lawrence Livermore National Laboratory
FEHM Vs. 1.0 1988	Multi-dimensional multiphase flow and transport of water, water vapor, non-condensable gases, dissolved solids, and heat in porous and fractured media; finite element method	Thermal-hydrologic and mass transport modeling of unsaturated and saturated zone; ground-water travel time calculations	Theory (Zyvoloski et al., 1988); verification (Zyvoloski and Dash, 1991); maintained at Los Alamos National Laboratory; see also FEHMAN
FEHMAN* Vs. N/A Oct 95	Multi-dimensional multiphase flow and transport of water, water vapor, non-condensable gases, dissolved solids, radionuclides, and heat in porous and fractured media; finite element method	Thermal-hydrologic and radionuclide transport modeling of unsaturated and saturated zone; ground-water travel time calculations	Theory (Zyvoloski et al., 1995a), user's manual (Zyvoloski et al., 1995b), verification and validation (Dash et al., 1995); maintained at Los Alamos National Laboratory; see also FEHM
FLAC* Vs. 3.22* Jun 93	Two-dimensional plastic deformation of soil, rock or other solid-material structures; finite difference method	Geomechanical analyses of ESF subsurface design and ESF tests	User's manual (Itasca, 1993a), qualification (CRWMS M&O, 1993f); maintained by Itasca Consulting Group, Inc.; see also FLAC3D
FLAC3D* Vs. 1.01* Jan 95	Three-dimensional plastic deformation of soil, rock or other solid-material structures; finite difference method	Geomechanical analyses of ESF subsurface design, including portal and opening stability	User's manual (Itasca, 1994b), vs. 1.01 qualification (CRWMS M&O, 1995k); maintained by Itasca Consulting Group, Inc.; see also FLAC
FRACMAN* Vs. N/A	Three-dimensional representation of geometry and hydrogeologic parameters for discrete fracture networks	Simulation of geometry and hydrogeologic characteristics of fracture networks in Yucca Mountain hydrogeologic units (input to MAFIC)	N/A

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
GENESIS* Vs. 2.01 1995	Global climate modeling	Provides regional boundary conditions for regional climate modeling by RegCM2	User's manual (Pollard and Thompson, 1995), validation (Thompson et al., in prep.); maintained by National Center for Atmospheric Research
GENII GENII-S Vs. N/A 1993	Biosphere radionuclide transport and radiation doses to humans by direct exposure, ingestion, and inhalation	Pre- and postclosure radiological exposure and risk calculations	Theory (Napier and Peloquin, 1988); user's manual (SNL, 1993); maintained at Pacific Northwest National Laboratory
GWRAND working version 1996	Two-dimensional unsaturated ground-water particle tracking, random walk dispersion; semi-analytical method	Unsaturated zone ground-water travel time analyses	Theory (Lu, 1994), preliminary documentation (Altman et al., 1996a); maintained at Sandia National Laboratories
ITOUGH2* Vs. 2.2 Oct 96	Calculation of TOUGH2 parameter values by automatic calibration with measured data; inverse analysis technique	Design and analysis of field and laboratory experiments	User's manual (Finsterle, 1993), qualification (Finsterle et al., 1996); maintained at Lawrence Berkeley National Laboratory
JAC JAC2D* Vs. N/A 1993	Large deformation, temperature-dependent, quasi-static mechanics problems in two dimensions	Thermal-mechanical behavior of rock mass for north ramp design 2C package; also for setup of ESF thermal-mechanical tests	User's manual (Biffle, 1981); maintained at Sandia National Laboratories; see also JAC3D
JAC3D* Vs. N/A 1993	Large deformation, temperature-dependent, quasi-static mechanics problems in three dimensions	Thermal-mechanical behavior of rock mass for north ramp design 2C package; also for ESF single heater test as-built predictions	User's manual (Biffle, 1993); maintained at Sandia National Laboratories; see also JAC and JAC2D
LYNX System* Vs. 1.0* May 94 Vs. 1.1* Oct 94 Vs. 3.06* Jan 95 Vs. 3.10 1996 Vs. 4.4 Sep 96	Three-dimensional modeling of geologic features and mine design	Geology and underground design modeling support of ESF and repository development and design	User's manual (Lynx, 1994, 1996), vs. 1.0 qualification (CRWMS M&O, 1994e), vs. 1.1 qualification (CRWMS M&O, 1994f), vs. 3.06 qualification (CRWMS M&O, 1995m); maintained by Lynx Geosystems, Inc.

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
MACCS Vs. 1.5.11.1 Oct 93	Radiation doses to humans	Calculations of radiation doses to workers and the general public	Theory (Jow et al., 1990), user's manual (Chanin et al., 1990), programmer's manual (Rollstin et al., 1990), maintenance release (Chanin et al., 1993); maintained by U.S. Nuclear Regulatory Commission
MAFIC* Vs. N/A	Three-dimensional isothermal fluid flow in discrete fracture networks	Analysis of discrete fracture flow in Yucca Mountain hydrogeologic units	N/A
MCNP* Vs. 4.2* Mar 94 Vs. 4A* May 96	Three-dimensional criticality and shielding analysis for nuclear/radioactive systems; Monte Carlo technique	Criticality and shielding analyses in support of waste package, surface facility, and repository development and design	Theory (Briesmeister, 1993, 1995), primer (Harmon et al., 1994), vs. 4.2 qualification (CRWMS M&O, 1994g), vs. 4A qualification (CRWMS M&O, 1996rr); maintained at Los Alamos National Laboratory
MLAEM Vs. 4.0 1995	Two-dimensional and quasi-three-dimensional saturated ground-water flow; analytical element method	Regional saturated ground-water flow analysis to establish boundary conditions for site-scale saturated zone modeling in support of site characterization	Basic theory (Strack, 1989; Haitjema, 1995), user's manual (Strack, 1992a); maintained by Strack Engineering; see also SLAEM
MODFLOW MODFLOWP Vs. N/A 1988	Two-dimensional and quasi-three-dimensional saturated ground-water flow; finite difference method	Regional and site-scale saturated ground-water flow analysis in support of site characterization	Documentation (McDonald and Harbaugh, 1988); maintained by U.S. Geological Survey
MPSalsa working version in preparation	Two-dimensional two-phase (gas/liquid) flow in heterogeneous porous media; finite element method	Thermal-hydrological modeling of unsaturated zone air and water flow	Theory (Shadid and Moffat, in prep.); user's manual (Shadid et al., in prep.); maintained at Sandia National Laboratories
NUFT Vs. 1.0 1995	Three-dimensional multiphase flow and transport of water, water vapor, gas, dissolved solids, radionuclides, and heat; integrated finite difference method	Thermal-hydrologic modeling of unsaturated and saturated zone in support of site characterization, engineered barrier system design studies, and performance assessments	Reference manual (Nitao, 1995); maintained at Lawrence Livermore National Laboratory

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
ORIGEN ORIGEN2 Vs. N/A 1973	Build-up and decay of radioisotopes in nuclear fission reactor and in spent fuel after removal from reactor, including associated heat generation	Generation of list, weight, and radioactivity of radionuclides and of heat generated in support of MGDS development and design and performance assessments	Theory (Bell, 1973); maintained at Oak Ridge National Laboratory
OS3D/GIMRT Vs. 1.0 Dec 95	Multi-dimensional multicomponent reactive mass transport	Reactive mass transport modeling (water chemistry, porosity/permeability, and mineralogy) of the altered zone and repository near field	User's and programmer's manual (Steefel and Yabusaki, 1995); maintained at University of South Florida, modified at Lawrence Livermore National Laboratory
PATH Vs. 88A 1988	Gamma shielding analysis for three-dimensional source-shield configuration; point-kernel integration technique	Calculation of gamma dose rates from waste packages and support of MGDS shielding development and design	Theory and user's manual (Su et al., 1987), validation (Boshoven, 1991); qualification (Su, in prep.); maintained by General Atomics
PIGS working version in preparation	Pitting corrosion of waste package containers	Interpretation of pitting corrosion experiments, potential component of waste package and total system performance assessment models	Theory (Henshall, in prep.); being developed at Lawrence Livermore National Laboratory
RegCM2* Vs. N/A 1995	Regional climate model	Provides boundary conditions for modeling future net infiltration at Yucca Mountain	Validation (Thompson et al., 1995); component of GENESIS; maintained by National Center for Atmospheric Research
RIP Vs. 4.05 1996	Total system postclosure performance assessment for radionuclide releases to accessible environment and radiation doses to the public	Total system postclosure performance assessments	Theory and user's manual (Golder, 1996), verification (Golder, 1995); maintained by Golder Associates, Inc.
SATTRAK working version 1996	Three-dimensional saturated ground-water particle tracking, random walk dispersion; finite element method	Saturated zone ground-water travel time analyses	Development aspects (Altman et al., 1996a); maintained at Sandia National Laboratories

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
SCALE System* Vs. 4.2* Jan 96	Criticality safety, shielding, heat transfer, and nuclear decay/fuel depletion analysis for nuclear facilities and waste package designs	Criticality, shielding, source term, and decay heat analysis in support of waste package development and design	Theory and user's manual (NRC, 1993; ORNL, 1995b), vs. 4.2 qualification (CRWMS M&O, 1996ss); maintained at Oak Ridge National Laboratory
SLAEM Vs. 3.0 1995	Two-dimensional single-layer saturated ground-water flow; analytical element method	Regional saturated ground-water flow analysis to establish boundary conditions for site-scale saturated zone modeling in support of site characterization	Basic theory (Strack, 1989; Haitjema, 1995), user's manual (Strack, 1992b); maintained by Strack Engineering; see also MLAEM
STAADIII/ISDS* Vs. 4-8MB, Rev. 16.0* Jun 93	Structural analysis and design, incl. columns, beams, and bracings for plane/space frame structures	Structural engineering analysis and design applications for plane trusses, plane frames, and space frames in the ESF	User's manual (Research Engineers, 1992), qualification (CRWMS M&O, 1993g); maintained by Research Engineers, Inc.
STAFF3D Vs. 2.0 1992	Multi-dimensional isothermal flow and radionuclide transport in anisotropic saturated porous and fractured media; finite element method	Hydrothermal analyses in support of site characterization	Theory (Huyakorn et al., 1992); maintained by HydroGeoLogic, Inc.
TOSPAC Vs. 1.10 1992	Radionuclide release from waste packages and one-dimensional, unsaturated isothermal water flow and radionuclide transport in fractured media; finite-difference method.	Input to total system postclosure performance assessments	Theory (Dudley et al., 1988), user's manual (Gauthier et al., 1992); maintained at Sandia National Laboratories
TOUGH TOUGH2* Vs. 1.11* Feb 96	Multi-dimensional multiphase flow and transport of water, water vapor, non-condensable gases, dissolved solids, radionuclides, and heat in porous and fractured media; integrated finite difference method	Thermal-hydrological modeling of unsaturated and saturated zone; ground-water travel time calculations; design of laboratory and in-situ thermohydrologic experiments	Theory and user's guide (Pruess, 1987; Pruess et al., 1991); TOUGH2 vs. 1.11 qualification (Pruess et al., 1996); conjugate gradient solvers (Moridis and Pruess, 1995); maintained at Lawrence Berkeley National Laboratory; see also A-TOUGH and V-TOUGH

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
TRACRN TRACR3D Vs. N/A 1991	Multi-dimensional isothermal liquid and gas flow and multi-component tracer/ radionuclide transport in porous and fractured media; finite difference method	Radionuclide transport modeling in support of site characterization; design of laboratory and in situ tracer experiments	Theory and user's manual (Travis, 1984; Travis and Birdsell, 1988; Birdsell and Travis, 1991); maintained at Los Alamos National Laboratory
TSA working version 1994	Collection of programs for total-system postclosure performance assessment for radionuclide releases to accessible environment	Total system postclosure performance assessments	Development aspects (Barnard et al., 1992; Wilson et al., 1994); maintained at Sandia National Laboratories
UDEC* Vs. 2.0* Mar 94	Two-dimensional response of discontinuous media (such as jointed rock mass) represented as an assemblage of discrete blocks; distinct element method	Analysis of underground openings (in jointed medium) subjected to in situ and seismic loadings in support of ESF and repository development and design	User's manual (Itasca, 1993b), vs. 2.0 qualification (CRWMS M&O, 1994h); maintained by Itasca Consulting Group, Inc.
UNWEDGE* Vs. 2.2* Jan 95	Three-dimensional analysis of geometry and stability of wedges defined by intersecting structural discontinuities in underground excavations, including rock bolts and shotcrete	ESF and repository excavation stability analyses	User's manual (Carvalho et al., 1992), vs. 2.2 qualification (CRWMS M&O, 1995m); maintained at University of Toronto
VNETPC* Vs. 3.1* Oct 93	Analysis of subsurface facility ventilation for mine networks, considering gaseous emissions, and design and cost analysis of ventilation equipment	Analysis and design of ESF and repository ventilation systems, including dust and diesel locomotive hydrocarbon exhausts	User's manual (Mine Ventilation Services, 1993), qualification (CRWMS M&O, 1993h); maintained by Mine Ventilation Services, Inc.
V-TOUGH* Vs. 7.8* Sep 95	Vectorized multi-dimensional multiphase flow and transport of water, water vapor, and heat in porous and fractured media; integrated finite difference method	Thermal-hydrologic modeling of unsaturated and saturated zone in support of thermal loading and engineered barrier system development and design	Theory and user's manual (Nitao, 1990); maintained at Lawrence Livermore National Laboratory; see also A-TOUGH and TOUGH/TOUGH2

Table I-1. Analytical Techniques (continued)

Name	Process	YMP Applications	Status
WAPDEG Vs. 1.0 Sep 96	Waste package degradation	Input to total system postclosure performance assessments	User's manual (Atkins and Lee, 1996).
WEEPTSA working version 1994	Probabilistic analysis of interaction of water flowing in discrete fractures with waste containers, radionuclide release, and transport to the water table	Input to total system postclosure performance assessments	In development; documentation (Barnard et al., 1992; Wilson et al., 1994); maintained at Sandia National Laboratories
YMIM Vs. 2.1 Apr 95	Radionuclide release from waste form and waste packages	Input to total system postclosure performance assessments; development and design of waste form and waste package experiments	User's manual (Gansemer and Lamont, 1995); maintained at Lawrence Livermore National Laboratories

Abbreviations and acronyms:

CD-ROM = compact disc - read-only memory
 CRWMS M&O = Civilian Radioactive Waste Management System
 Management and Operating Contractor
 ESF = Exploratory Studies Facility
 MGDS = mined geologic disposal system

N/A = not applicable or not available
 SNL = Sandia National Laboratories
 Vs. = version
 YMP = Yucca Mountain Site Characterization Project

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Table I-2. Cross-Reference between Modeling Descriptions and Progress Report Sections

Computer codes added since Progress Report #14 are shown in bold type. No computer codes were deleted.

Code Name	Description	Development & Improvement	Testing and Verification	Model Validation	Application
3DEC	Excavation rock mechanics				
ABAQUS	Soil and rock mechanics				
ANSYS	Thermal-mechanics		5.1.2		
AREST AREST-CT	Waste package degradation and radionuclide release		6.10.8		
A-TOUGH	V-TOUGH with atmospheric interaction				
CLIMATE	Drift ventilation analysis and design				
CLIMSIM	Drift climatic conditions				
COYOTE	Heat conduction and diffusion in solids				
DIPS	Geologic structure analysis and graphics				
DORT-2D TORT-3D	Neutron and photon transport				
Earthvision	Geologic modeling				
ELFPOINT	Rock deformation from shear and tensile faulting				
EQ3/6	Geochemical speciation, solubility, and reactions	6.10.5	3.2.4	5.2.2	5.2.2 6.9.1
FEHM FEHMN	Multiphase fluid and heat flow with radio-nuclide transport	3.2.14 6.8.1 6.8.3			3.1.6 3.1.15 3.2.14 6.8.2
FLAC FLAC 3D	Soil and rock mechanics				5.2.4
FRACMAN	Fracture network geometry and parameter analysis				
GENESIS	Global climate modeling				

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Table I-2. Cross-Reference between Modeling Descriptions and Progress Report Sections (continued)

Code Name	Description	Development & Improvement	Testing and Verification	Model Validation	Application
GENII GENII-S	Biosphere radionuclide transport and radiation doses				
GWRAND	Unsaturated zone ground-water particle tracking				
ITOUGH2	Calculation of TOUGH2 parameter values				
JAC JAC2D JAC3D	Large deformation mechanics				
LYNX	Modeling of geology and underground facility design				4.1.3 4.1.7
MACCS	Radiation doses to humans				
MAFIC	Fluid flow in discrete fracture networks				
MCNP	Criticality and shielding		5.1.2	5.1.3	5.1.3
MLAEM	Saturated ground-water flow				
MODFLOW MODFLOWP	Saturated ground-water flow				3.1.4
MPSalsa	Two-phase fluid and heat flow				
NUFT	Multiphase fluid and heat flow with radio-nuclide transport	5.2.1	3.14		5.2.3 5.2.4 6.8.2
ORIGEN ORIGEN2	Nuclear fuel decay and heat generation				5.1.3
OS3D/GIMRT	Multicomponent reactive mass transport		3.14		6.9.1
PATH	Gamma shielding analysis				
PIGS	Pitting corrosion	6.9.9			
RegCM2	Regional climate model				
RIP	Total system postclosure performance				6.8.1

Table I-2. Cross-Reference between Modeling Descriptions and Progress
Report Sections (continued)

Code Name	Description	Development & Improvement	Testing and Verification	Model Validation	Application
SATTRAK	Saturated zone ground-water particle tracking				
SCALE	Criticality, shielding, heat transfer, nuclear decay		5.1.2		
SLAEM	Saturated ground-water flow				
STAADIII/ISDS	Structural analysis of columns, beams, frames				
STAFF3D	Saturated ground-water flow and radionuclide transport				
TOSPAC	Unsaturated zone flow, waste package radionuclide release, and radionuclide transport				
TOUGH TOUGH2	Multiphase fluid and heat flow with radionuclide transport	3.1.13			6.8.2 6.12.5
TRACRN TRACR3D	Liquid and gas flow with radionuclide transport				
TSA	Total system postclosure performance				
UDEC	Jointed-rock mechanics				
UNWEDGE	Jointed-rock mechanics				
VNETPC	Ventilation of underground excavations				
V-TOUGH	Multiphase fluid and heat flow				5.2.3 6.8.2
WAPDEG	Waste package barrier degradation and corrosion	6.10.8			
WEEPSTA	Probabilistic discrete fracture ground-water flow				
YMIM	Waste package radionuclide release	6.9.10 6.10.8	6.10.8		6.10.3 6.10.9

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APPENDIX J

Glossary

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APPENDIX J

Glossary

Accessible environment means the atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the controlled area.

Advanced conceptual design (ACD) means the design phase that will be used to explore selected design alternatives and will firmly fix and refine the design criteria and concepts to be made final in later design efforts. The project feasibility will be demonstrated, life-cycle costs estimated, preliminary drawings prepared, and a construction schedule developed as required by U.S. Department of Energy Order 6410.1.

Advection means transport that results from macroscopic fluid flow.

Aquifer means a formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield sufficient quantities of water to wells and springs.

Areal mass loading means the amount of heavy metal (usually expressed in metric tons of uranium or equivalent) emplaced per unit area in the proposed repository.

Backfill means (1) The general fill that is placed in the excavated areas of the underground facility. Backfill materials may be either excavated tuff or other earthen materials. (2) The material or process used to refill an excavation.

Barrier means any material or structure that prevents or substantially delays the movement of water or radionuclides.

Borehole means a hole made with a drill, auger, or other tools for exploring strata in search of minerals, supplying water for blasting, emplacing waste, proving the position of old workings or faults, or releasing accumulations of gas or water. Boreholes include core holes, dry-well-monitoring holes, waste-emplacement boreholes, and test holes for geophysical or ground-water characterization.

Bulk permeability means volume-averaged permeability. See "permeability."

Burnup means a measure of nuclear-reactor fuel consumption expressed either as the percentage of fuel atoms that have undergone fission or as the amount of energy produced per unit weight of fuel.

Canister is a metal receptacle with the following purpose: (1) for solidified high-level radioactive waste, its purpose is a pour mold, and (2) for spent fuel, it may provide structural support for loose rods, nonfuel components, or confinement of radionuclides during preclosure operations.

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Cladding means the metallic outer sheath of a fuel element, generally made of stainless steel or a zirconium alloy.

Closure means final backfilling of the remaining open operational areas of the underground facility after the termination of waste emplacement, culminating in the sealing of shafts.

Confinement as it pertains to radioactivity, means the retention of radioactive material within some specified bounds. Confinement differs from containment in that there is no absolute physical barrier in the former.

Contact (geology) means a plane or irregular surface between two different types or ages of rocks.

Containment means the confinement of radioactive waste within a designated boundary.

Controlled area means a surface location, to be marked by suitable monuments, extending horizontally no more than 10 kilometers in any direction from the outer boundary of the underground facility, and the underlying subsurface, which area has been committed to use as a geologic repository and from which incompatible activities would be prohibited before and after permanent closure.

Core science means those disciplines capable of providing information and data needed to address the major unresolved technical questions regarding the conceptual design of the repository and/or its expected performance in the geologic setting.

Criticality means the condition of supporting a nuclear chain reaction. It occurs when the number of neutrons present in one generation cycle equals the number generated in the previous cycle.

Defense high-level nuclear waste means the high-level waste generated in the course of national defense activities.

Diffusion means transport that results from random thermal motion of molecules.

Dispersion means the solute-spreading or dilution phenomena caused by mechanical mixing during ground-water movement and molecular diffusion.

Disposal means the emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste, and the isolation of such waste from the accessible environment.

Disposal container is a vessel consisting of the barrier materials and internal components designed to meet disposal requirements, into which the uncanistered or canistered waste form will be placed.

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Drawdown means the lowering of the water table or potentiometric surface caused by pumping.

Drift means a horizontal or nearly horizontal, mined passageway.

Emplacement means the act of placing waste containers in prepared positions.

Engineered barrier system means the waste packages and the underground facility.

Environmental impact statement means the document required by Section 102(2)(C) of the National Environmental Policy Act of 1969. Sections 114(a) and 114(f) of the Nuclear Waste Policy Act of 1982 include certain limitations on the National Environmental Policy Act requirements as they apply to the preparation of an environmental impact statement for the development of a repository at a characterized site.

Exploratory studies facility means a facility constructed for the purpose of performing underground studies during site characterization.

Fault means a fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture or zone of fractures.

Finite-element computer code means a computer code that uses the finite-element method. The finite-element method is a method of numerical analysis that divides a region of interest into discrete elements and represents the behavior of the elements with a set of simultaneous equations. Solution of the set of equations yields the behavior at discrete points within the region of interest.

Flow path means the theoretical line that ground water follows in moving from a recharge area to a discharge area.

Flux means the volume of fluid per unit area per unit time. Also known as specific discharge.

Fracture is a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints, and faults.

Geochemistry means the study of the distribution and amounts of the chemical elements in minerals, ores, rocks, soils, water, and the atmosphere and the chemical interactions between these phases.

Geologic repository means a system, requiring licensing by the U.S. Nuclear Regulatory Commission, that is intended to be used, or may be used, for the permanent disposal of radioactive waste (including spent nuclear fuel) in excavated geologic media. A geologic repository includes (1) the geologic repository operations area and (2) the portion of the geologic setting that provides isolation of the radioactive waste and is located within the controlled area.

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Geomechanics means the branch of geology that deals with the response of earth materials to deformational forces and embraces the fundamentals of structural geology.

Ground-water flux means the rate of ground-water flow per unit area of porous or fractured media measured perpendicular to the direction of flow.

Ground-water travel time means the time required for a unit volume of ground water to travel between two locations. The travel time is the length of the flow path divided by the velocity, where velocity is the average ground-water flux passing through the cross-sectional area of the geologic medium through which flow occurs, perpendicular to the flow direction, divided by the effective porosity along the flow path. If discrete segments of the flow path have different hydrologic properties, the total travel time will be the sum of the travel times for each discrete segment.

Guidelines means Part 960 of Title 10 of the Code of Federal Regulations—General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories.

High-level radioactive waste means (1) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (2) other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation.

Hundred-year storm means a storm whose intensity is such, on a statistical basis, that it is expected to recur only once every 100 years.

Hydrogeologic properties means the properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.

Hydrologic unit means any soil or rock unit or subsurface zone that affects the storage or movement of ground water by its porosity or permeability.

In situ means in its natural or original position. The phrase distinguishes in-place experiments, conducted in an underground facility from those conducted in the laboratory.

Infiltration means the flow of a fluid into a substance through pores or small openings. It connotes flow into a substance as opposed to the word percolation, which connotes flow through a substance.

Invert has two meanings on the Project. Its general meaning is the low point of something such as a tunnel, drift or drainage channel. However, as mostly used herein, invert means an engineered structure or material placed on excavated drift floors (the low points) to serve as structural support for drift transportation or emplacement systems. (For precast concrete, the proper name is invert segments, but they are commonly referred to simply as inverts.) Typical

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invert (segments) convert rounded excavated floors to flat level surfaces for transportation system use. Emplacement drift inverts may be specially designed to enhance the waste isolation and criticality prevention capabilities of the proposed repository through choice of invert materials or invert shape. Inverts may also be used to help channel water to improve repository drainage.

Issue means a question relating to the performance of the mined geologic disposal system that must be resolved to demonstrate compliance with the applicable Federal regulations (including 10 CFR Part 60, 10 CFR Part 960, applicable Environmental Protection Agency standards, and 10 CFR Part 20).

Isolation means inhibiting the transport of radioactive material so that the amounts and concentrations of this material entering the accessible environment will be kept within prescribed limits.

License application means an application for a license from the U.S. Nuclear Regulatory Commission to construct a repository.

Lithophysae means voids in rocks composed of concentric shells of finely crystalline alkali feldspar, quartz, and other materials that were formed due to entrapped gas that later escaped.

Maximally exposed individual means a hypothetical person who is exposed to a release of radioactivity in such a way that he receives the maximum possible individual radiation dose or dose commitment. For instance, if the release is a puff of contaminated air, the maximally exposed individual is a person at the point of the largest ground-level concentration and stays there during the whole time the contaminated-air cloud remains above. This term is not meant to imply that there really is such a person; it is used only to indicate the maximum exposure a person could receive.

Metric tons heavy metal means metals with high atomic numbers which are loaded into nuclear reactors to take part in chain reactions. Examples of heavy metals include thorium, uranium, plutonium, and neptunium. When used in the Civilian Radioactive Waste Management Program, the term usually refers to the mass of heavy metal in spent fuel which was present when the fuel was initially loaded into a reactor. (A metric ton is a unit of mass equal to 1000 kg.)

Mined geologic disposal system means a system, requiring licensing by the U.S. Nuclear Regulatory Commission, that is used for the disposal of high-level radioactive waste in excavated geologic media. It is synonymous with "geologic repository."

Multibarrier system means a system of natural and engineered barriers, operating independently or relatively independently, that acts to contain and isolate the waste.

Multi-purpose canister means a sealed, metallic canister holding multiple spent nuclear fuel assemblies in a dry, inert environment and overpacked separately and uniquely for the various system elements of storage, transportation, and disposal.

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National Environmental Policy Act means the Federal statute that is the national charter for protection of the environment. The Act is implemented by procedures issued by the Council on Environmental Quality and the DOE. The National Environmental Policy Act of 1969 appears at 42 U.S.C. 4321 et seq.

Natural barrier means the physical, mechanical, chemical, and hydrologic characteristics of the geologic environment that individually and collectively act to minimize or preclude radionuclide transport.

Natural system means a host rock suitable for repository construction and waste emplacement and the surrounding rock formations. It includes natural barriers that provide containment and isolation by limiting radionuclide transport through the geohydrologic environment to the biosphere and provide conditions that will minimize the potential for human interference in the future.

Near field means the region where the natural geohydrologic system has been significantly perturbed by the excavation of the repository and the emplacement of the waste.

Net infiltration means infiltration minus water lost to evapotranspiration and other processes such as circulation of air within the rock mass.

Notice of intent means a notice published in the Federal Register that an environmental impact statement will be prepared and considered by a Federal agency. The notice is required by the National Environmental Policy Act implementing procedures. The notice must describe the proposed action and possible alternatives; describe the agency's proposed scoping process including whether, when, and where any scoping meeting will be held; and state the name of an agency official who can answer questions about the proposed action and the environmental impact statement.

Nuclear Waste Policy Act (42 USC 10101 et seq.) means the Federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management and defined its mission to develop a Federal system for the management and geologic disposal of commercial spent nuclear fuel and other high-level radioactive wastes, as appropriate. The Act also specified other Federal responsibilities for nuclear waste management, established the Nuclear Waste Fund to cover the cost of geologic disposal, authorized interim storage under certain circumstances, and defined interactions between Federal agencies and the states, local governments, and Indian tribes. The act was amended in 1987 and 1992.

Perched ground water means unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. Perched ground water is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

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Percolation means the passage of a liquid through a porous substance (e.g., the movement of water, under hydrostatic pressure developed naturally underground, through the interstices and pores of the rock or soils.)

Percolation flux means volume of water moving downward and/or laterally through the unsaturated zone in a given time period.

Performance assessment means any analysis that predicts the behavior of a system or system component under a given set of constant and/or transient conditions. Performance assessments will include estimates of the effects of uncertainties in data and modeling.

Performance confirmation means the program of tests, experiments, and analyses that is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure can be met.

Permeability means the capacity of a medium like rock, sediment, or soil to transmit ground water. Permeability depends on the size and shape of the pores, joints, and fractures in the medium and the manner in which they are interconnected.

Postclosure means the period of time after the closure of the geologic repository.

Preclosure means the period of time before and during the closure of the geologic repository.

Primary area means the surface location, as indicated on a map, of the principal area that may be suitable for waste emplacement. When projected downward along the location of faults and other geologic features, the boundaries of the primary area encompass the principal region within the target emplacement horizon that is considered potentially suitable for waste emplacement.

Radioactive waste or "waste" means high-level radioactive waste and other radioactive materials, including spent nuclear fuel, that are received for emplacement in a geologic repository.

Repository construction means all excavation and mining activities associated with the construction of shafts, shaft stations, rooms, and necessary openings in the underground facility, preparatory to radioactive-waste emplacement, as well as the construction of necessary surface facilities, but excluding site-characterization activities.

Repository horizon means the horizontal plane within the host rock where the location of the proposed repository is planned.

Rock bolt means a bar, usually constructed of steel, that is anchored into predrilled holes in rock as a support device.

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Saturated zone means that part of the Earth's crust beneath the water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

Seal means an engineered barrier to prevent radionuclide migration or the intrusion of undesirable substances.

Seepage means portion of percolation flux entering the emplacement drifts in a given time period.

Seismic means pertaining to, characteristic of, or produced by earthquakes or earth vibrations.

Shallow infiltration means water that has percolated to a depth of at least 2 meters into the bedrock closest to the surface. Two meters is usually assumed to be below the zone of substantial evapotranspiration.

Site means a potentially acceptable site or a candidate site, as appropriate, until such time as the controlled area has been established, at which time the site and the controlled area are the same.

Site characterization means activities, whether in the laboratory or in the field, undertaken to establish the geologic conditions and the ranges of the parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavations of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken.

Sorption is a term including both adsorption and absorption, and means the binding, on a microscopic scale, of one substance to another, such as by adsorption or ion exchange. In this document, the word is especially used for the sorption of dissolved radionuclides onto aquifer solids or waste-package materials by means of close-range chemical or physical forces.

Spent nuclear fuel means fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

Stakeholders means individuals or organizations who have an important, ongoing interest in the service and service quality of the Office of Civilian Radioactive Waste Management.

Stoichiometry means (1) the application of the laws of definite proportions and of the conservation of matter and energy to chemical activity; (2) the quantitative relationship between constituents in a chemical reaction.

Storativity means the volume of water released from storage in a vertical column of unit area when the water table or other piezometric surface declines 1 unit of height. In an undefined aquifer, it is approximately equal to the specific yield.

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Stratigraphy is the branch of geology that deals with the definition and interpretation of the rock strata, the conditions of their formation, character, arrangement, sequence, age, distribution, and especially their correlation by the use of fossils and other means of identification.

Substantially complete containment means that containment of the radionuclides enclosed within the waste packages is substantially complete for 1000 years (with less than 1 percent of the waste packages failing within 1000 years after permanent closure of the geologic repository) and with a mean waste package lifetime well in excess of 1000 years.

Surface facilities means repository support facilities within the restricted area.

Systems engineering systemically applies science and engineering principles to control a complex total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process that transforms and integrates operational needs and requirements into a description of system requirements to maintain the overall system effectiveness.

Thermal loading means the application of heat to a system, and is usually measured in terms of watt density. The thermal loading for a repository is the watts per acre produced by the radioactive waste in the active disposal area.

Thermogravimetric analysis means a method of analysis that measures the loss or gain of weight by a substance as the temperature of the substance is raised or lowered at a constant rate.

Tracer testing means a procedure in which a soluble substance (tracer) is added to ground water at one location and its movement to another location is observed. Tracer testing is a technique by which ground-water flow directions and velocities and other hydrologic properties of rocks can be estimated.

Transmissivity means the rate at which water of the prevailing kinematic viscosity is transmitted through a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the thickness of the aquifer.

Tuff means a rock formed of compacted volcanic ash and dust.

Unsaturated zone means the zone between the land surface and the water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.

Viability assessment means an Office of Civilian Radioactive Waste Management Program judgment about the prospects for geologic disposal at the Yucca Mountain site, based on repository and waste package designs, a total system performance assessment, a licensing completion plan, and repository cost and schedule estimates.

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Waste package means the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container.

10 CFR Part 60 means the Nuclear Regulatory Commission regulation, titled "Disposal of High-Level Radioactive Wastes in Geologic Repositories," that sets forth technical requirements governing development of a permanent geologic repository for spent nuclear fuel and high-level radioactive waste sited, constructed, and operated in accordance with the Nuclear Waste Policy Act of 1982.

10 CFR Part 960 means the Department of Energy regulation, titled "General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories," that establishes guidelines for use by the Secretary of Energy in evaluating the suitability of sites for the development of nuclear waste repositories.

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APPENDIX K

Acronyms, Abbreviations, and Symbols

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESF	Exploratory Studies Facility
FY	fiscal year
MGDS	Mined Geologic Disposal System
M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
NRC	U.S. Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
Program	Civilian Radioactive Waste Management Program
Project	Yucca Mountain Site Characterization Project
QA	quality assurance
SCP	Site Characterization Plan
USGS	U.S. Geological Survey
YMSCO	Yucca Mountain Site Characterization Office

Miscellaneous Terms, Units, and Designators

atm	atmosphere (pressure)
AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Materials
ATM	approved test material
darcy	a measure of the permeability of a porous medium; $1 \text{ darcy} = 9.87 \times 10^{-13} \text{m}^2$
Eh	oxidation potential, also called redox potential, of a chemical element, expressed in volts or millivolts
gpm	gallons per minute
ka	kiloannum (thousand years ago)
ky	thousand years
Ma	mega-annum (million years ago)
pH	the negative common logarithm of the hydrogen ion concentration of a solution; a measure of the acidity or alkalinity of the solution
ppb	parts per billion
ppm	parts per million
UNS	Unified Numbering System for Metals and Alloys

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

Borehole Letter Designators

c	Hydrologic test hole
G	Geologic
GA	Geologic Angle "exploratory hole"
GU	Geologic Unsaturated zone
h	Horizontal drilled hole
H	Hydrologic Research Facility holes
HPF	Hydrologic Properties of Faults
J	Jackass Flats (water wells)
N	Neutron hole
NRG	North Ramp Geologic hole
ONC	Oversight Nye County
p	Paleozoic or pre-Tertiary hole
RBT	Radial Borehole Tests
RF	Repository Surface Facility hole
SD	Systematic Drilling hole
SRG	South Ramp Geologic hole
UE	Underground Exploratory
USW	Underground Southern (Nevada) Waste hole
UZ	Unsaturated Zone hole
UZN	Unsaturated Zone Neutron hole
V	Volcanic hole
VH	Volcanic/Hydrologic hole
WT	Water Table hole

Hydrogeologic Unit Names

CFu	Crater Flat unit
CHn	Calico Hills nonwelded unit
PTn	Paintbrush nonwelded unit
TCw	Tiva Canyon welded unit
TSw	Topopah Spring welded unit

ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

SI and Metric Units

°C	degree Celsius
cm ³	cubic centimeter
cm	centimeter (= 10 ⁻² m or 0.3937 inch)
d	day
g	gram (= 0.03527 ounce)
GWd	gigawatt-day
h	hour
ha	hectare (= 2.48 acres)
Hz	hertz (cycles per second)
J	joule (newton-meter)
K	degree kelvin
kg	kilogram (= 10 ³ grams or 2.2046 pounds)
kWh	kilowatt-hour
km	kilometer (= 10 ³ m or 0.6214 mile)
L	liter (= 0.2642 gallon)
MTU	metric tons of uranium equivalent
MTIHM	metric tons of initial heavy metal
m	meter (= 3.2808 feet)
mg	milligram (= 10 ⁻³ g)
mgal	milligalileo
mL	milliliter (= 10 ⁻³ L)
mm	millimeter (= 10 ⁻³ m)
μm	micrometer (= 10 ⁻⁶ m)
MWd	megawatt-day
MWh	megawatt-hour
nm	nanometer (= 10 ⁻⁹ m)
nT	nanotesla (= 10 ⁻⁹ tesla)
Pa	pascal (also, MPa = megapascal, kPa = kilopascal)
S	siemens
s	second
V	volt
W	watt

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APPENDIX L

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Note to Readers

To meet the requirements of Federal Executive Order 12906, the following information is provided:

"Map number YMP-96-152.0 was compiled on September 11, 1996 by the M&O/TRW Technical Data Management GIS Section. Source documentation for the data sets included in this map are available upon request."

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