***Repository Safety Strategy:
U.S. Department of Energy's
Strategy to Protect Public Health and
Safety After Closure of a Yucca Mountain
Repository***

Revision 1

January 1998

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

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FOREWORD

This document presents the U.S. Department of Energy's updated strategy to protect public health and safety after closure of a Yucca Mountain repository. It describes the process for iteratively developing the postclosure safety case for a potential repository system at Yucca Mountain. This document will be updated as new site, design, and performance information dictates, or when regulatory changes provide impetus for rethinking aspects of the strategy.

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CHANGE HISTORY

<u>REV. NO.</u>	<u>ICN NO.</u>	<u>EFFECTIVE DATE</u>	<u>DESCRIPTION OF CHANGE</u>
0		July 1996	Initial issue of strategy, preliminary predecisional draft
1		January 1998	Revise statement of strategy, revise title

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SUMMARY

The updated Strategy to Protect Public Health and Safety explains the roles that the natural and engineered systems are expected to play in achieving the objectives of a potential repository system at Yucca Mountain. These objectives are to contain the radionuclides within the waste packages for thousands of years, and to ensure that annual doses to a person living near the site will be acceptably low. This strategy maintains the key assumption of the *Site Characterization Plan* (DOE 1988) strategy that the potential repository level (horizon) will remain unsaturated. Thus, the strategy continues to rely on the natural attributes of the unsaturated zone for primary protection by providing a setting where waste packages assisted by other engineered barriers are expected to contain wastes for thousands of years. As in the *Site Characterization Plan* (DOE 1988) strategy, the natural system from the walls of the underground openings (drifts) to the human environment is expected to provide additional defense by reducing the concentrations of any radionuclides released from the waste packages.

The updated Strategy to Protect Public Health and Safety is the framework for the integration of site information, repository design and assessment of postclosure performance to develop a safety case for the viability assessment and a subsequent license application. Current site information and a reference design are used to develop a quantitative assessment of performance to be compared with a performance measure. Four key attributes of an unsaturated repository system that are critical to meeting the objectives:

- Limited water contacting the waste packages
- Long waste package lifetime
- Slow rate of release of radionuclides from the waste form
- Concentration reduction during transport through engineered and natural barriers

These attributes are evaluated by summarizing current knowledge and stating remaining issues in the form of testable hypotheses. Each attribute is influenced by natural processes and the placement of engineered components—multiple natural and engineered barriers. This meeting of functional requirements by multiple barriers provides defense in depth. Iteration among the site, design, and performance assessment teams produces an evolving picture of what site information and design features are important to performance. This is the process that guides development of the safety case. The safety case is the set of arguments that will be made to show that the repository system will contain and isolate waste sufficiently to protect public health and safety. Underpinning this set of arguments is an understanding of the performance of the repository system. This updated Strategy to Protect Public Health and Safety is the framework to define that understanding.

1. INTRODUCTION

The original strategy to protect public health and safety at the Yucca Mountain site was described in the *Site Characterization Plan* (DOE 1988). Since that time, much has been learned about the site, and the engineered system design has matured, providing better understanding of the performance of the combined natural and engineered systems.

Characterization of the site and design of the engineered systems have continued against the backdrop of a changing regulatory framework. The *Site Characterization Plan* strategy was developed to address the

This updated strategy incorporates:

- Recent site characterization information
 - New repository and waste package designs
 - Improved performance predictions
 - Changing regulatory framework
-

U.S. Nuclear Regulatory Commission's Technical Criteria (10 CFR 60, *Disposal of High-level Radioactive Wastes in Geologic Repositories*) and the standard promulgated by the U.S. Environmental Protection Agency in 1985 (40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-level and Transuranic Radioactive Wastes*).

The *Energy Policy Act of 1992* directed the Environmental Protection Agency to promulgate a site-specific dose- or risk-based radiation protection standard for Yucca Mountain to replace the release-based standard in Part 191, and the Nuclear Regulatory Commission to conform their regulations to this new standard. This standard is currently in preparation. Until this regulatory guidance is available, the Department of Energy has established an interim performance measure and goal. The interim performance measure is that the expected dose rate to an average individual in a critical group living 20 km from the repository not exceed 25 mrem/year from all pathways and all radionuclides during the first 10,000 years after closure. Doses are to be evaluated beyond 10,000 years, with a goal of not exceeding the 10,000 year measure, but recognizing the increasing uncertainty of these longer term analyses. The Department of Energy considers that 20 km from the repository is a reasonable location for considering groundwater to be accessible for household and very limited agricultural uses.

In this updated strategy, the attributes of the unsaturated zone environment are relied upon to provide a setting where waste packages and other engineered barriers are expected to prevent the contact of radionuclides in the waste by groundwater for thousands of years. The strategy further addresses the case where waste packages are breached and multiple natural barriers are relied upon to limit radionuclide movement and concentration. Using this updated strategy, testing and analysis can focus on those features of the natural and engineered systems that are most important to the safety of the potential repository. A schematic of the current concept for the repository is shown in Figure 1.

2. FUNDAMENTAL CONCEPTS IN THE UPDATED STRATEGY

The Strategy to Protect Public Health and Safety explains the roles that the natural and engineered systems of a potential Yucca Mountain repository are expected to play in achieving the objectives of the repository system. It describes the iterative process for developing a postclosure safety case for the viability assessment in 1998, and later a license application to be submitted to the Nuclear Regulatory Commission. This updated strategy is not a safety case. Instead it lays out the technical basis and process used for integrating site information, design analyses, and performance assessment to define and support a safety case (Figure 2).

The safety case will be the set of arguments that will be made to show that the repository system will contain and isolate waste sufficiently to protect public health and safety. These arguments will include estimates of the expected performance of the system, consideration of effects of unanticipated processes and events; descriptions of various approaches to defense in depth, including multiple barrier systems, to mitigate uncertainties in site characteristics and future changes in the system; understanding from relevant natural analogues to this site, and a performance confirmation program. Underpinning this set of arguments is an understanding of the physical performance of the repository system. This Strategy to Protect Public Health and Safety is the framework to define that understanding.

This strategy maintains the core of the *Site Characterization Plan* (DOE 1988) strategy: a fundamental assumption that the potential repository horizon will remain unsaturated. Advantages of a repository in the unsaturated zone at Yucca Mountain were pointed out by the U.S. Geological Survey in 1982 (written correspondence USGS to DOE, Feb. 5, 1982). In unsaturated rock, openings do not fill with water, and it is feasible to consider preventing water from contacting the waste packages. Thus, the updated strategy

shown by past assessments to be most important to developing a safety case for a potential repository in unsaturated tuff at Yucca Mountain:

- Limited water contacting the waste packages
- Long waste package lifetime
- Slow rate of release of radionuclides from the waste form
- Concentration reduction during transport through engineered and natural barriers.

The following discussion describes the approach for evaluating each key performance attribute by summarizing the current evidence and identifying the remaining issues in the form of testable hypotheses. The approaches to testing and analyses that can be used to evaluate the hypotheses are reviewed at the end of this discussion (Section 5).

3.1 LIMITED WATER CONTACTING THE WASTE PACKAGES

Performance assessments have shown that the amount of water contacting the waste packages is the most important determinant of the ability of the site to contain and isolate waste (CRWMS M&O 1995). This process ultimately affects all aspects of performance from waste package lifetime to radionuclide movement. The original conceptual model for the Yucca Mountain flow system was developed more than 10 years ago—an updated schematic representing this model is provided in Figure 4. Site characterization information gained since the original model was developed provides general support for most of the early conceptual ideas of how a Yucca Mountain repository would function.

The amount of water contacting the waste packages is limited by the seepage into the repository, which depends on the nature of percolation in the repository host rock which depends, in turn, on precipitation at the surface, the amount of this precipitation infiltrating into the mountain, and the redistribution of the water as it percolates down to the host rock. The amount of precipitation at the surface has been monitored for several decades and currently averages about 170 mm/year (about 6 inches/year). The precipitation has been

periodically higher in the past and is expected to be periodically higher in the future. Studies indicate that climate changes leading to as much as 500 mm/year precipitation in the future may need to be considered at the site. Net infiltration currently averages about 6 mm/year at the site and may have averaged more than 30 mm/year in some periods over the past 20,000 years (*Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada*. Flint, A.L., Hevesi, J.A., and Flint, L.E., in editorial review. Yucca Mountain Project Milestone Report 3GUI623M. Denver, Colorado: U.S. Geological Survey).

Net infiltration - the portion of precipitation that penetrates and remains in the rock

Percolation flux - volume of water moving downward through the unsaturated zone in a given time period

Seepage - portion of percolation flux entering the emplacement drifts in a given time period

The redistribution of the water as it proceeds to depth is known generally but not in detail. There is evidence that the flow generally proceeds downward and is distributed among various fractures in the host rock and possibly in the rock matrix. Some of this flow is expected to be sporadic, reflecting the episodic nature of storms at the surface. Other components of the flow are expected to be more constant in time, resulting from mediation of the episodic flows by variation in hydrologic properties and fracture densities within and between various welded and nonwelded tuff layers, such as the PTn unit (see Figure 4). There

is evidence that some of the flow occurs in fast flow paths in which the flux reaches the repository horizon in less than 50 years (Fabryka-Martin et al. 1997). Some of the flow takes longer, possibly thousands of years. The percolation can be diverted laterally to some degree due to the contrasts in hydrologic properties. Such diversion could lead to concentration of flow in the fast paths. Although site investigations have determined that all of these effects are potentially important at the site, detailed allocation of the flow among these processes is not necessary for performance assessment. At the present time, information is sufficient to estimate average fluxes and spatial and temporal variations in the host rock (Bodvarsson et al. 1997).

The amount of seepage into drift openings can be limited by the tendency for the water, due to capillary forces, to remain in the small pores and fracture networks of the rock and thus flow around the drift openings, rather than into them. Performance assessment results show this diversion effect could be important. Until specific measurements are available, bounding values will be used.

Heat from the radioactive waste can mobilize water in the host rock and drive this water away from the repository (Buscheck 1996). Some of the water mobilized while the temperatures are high will drain away below the repository, but some may be retained above the repository and return in a few thousand years after the temperatures decrease. If the water does not return, or if the return flow is through the matrix and rewetting is therefore very slow, percolation after the thermal pulse could be less than under present conditions for thousands of years. If the water returns quickly, local percolation fluxes higher than present conditions could occur, and some areas of the repository may not be dry. It is possible that hydrothermal reactions will irreversibly change the hydraulic properties of the rock due to either mineral alteration or silica (SiO_2) dissolution and redeposition, thus affecting the percolation flux.

Figure 4. Conceptual model of flow at the Yucca Mountain site (modified from Montazer and Wilson 1984).

Regardless of the origin of the percolation flux, engineered barriers can protect the waste packages from water contact if seepage should enter the drifts. The waste packages are designed to delay corrosion, and if necessary, could be further protected by drip shields, backfill, ceramic coatings, and the opening support structure. These barriers depend on the characteristics of the unsaturated zone environment for their performance.

The specific hypotheses to be addressed regarding limited water contact are as follows:

1. Percolation flux at repository depth can be bounded.
2. Seepage into the emplacement drifts will be a fraction of the percolation flux.
3. Bounds can be placed on thermally induced changes in seepage rates.
4. The amount of seepage that contacts waste packages can be limited.

3.2 LONG WASTE PACKAGE LIFETIME

As long as waste packages remain intact, the waste will be completely contained and prevented from any contact with the host rock, air, or groundwater. This containment has several positive results. The radiation source is reduced due to radioactive decay. Uranium dioxide is protected from contact with air while it is at a high temperature making it susceptible to oxidation (Section 3.3). In addition, the waste is protected during the period of greatest uncertainty about processes operating in the repository—the initial thermal period.

Test and modeling information that is already available indicates that containment times exceeding 1,000 years may be achievable. The assessments show that the waste package containment time depends directly on the temperature, humidity, and other environmental conditions within the emplacement drift. Designs are being developed to increase the containment time, while taking the expected environments into account. The current waste package reference design is double-walled with a thick corrosion-allowance outer barrier surrounding a corrosion-resistant inner barrier. This design approach provides redundancy because the outer barrier delays exposure of the inner barrier to humid or aqueous environments that can cause corrosion. A double-walled waste package also may offer some degree of galvanic protection of the inner barrier by the outer barrier if a suitable design and materials are chosen. These effects have the potential to extend the lifetime of the inner barrier for a significant time. However, the basis for these long-term predictions remains short-term measurements.

During the first few thousand years, heat is expected to dominate processes in the repository. The heat will mobilize water, drive chemical reactions, and alter the host rock. Property changes could be either potentially deleterious or helpful. Heat has the potential to dry the waste packages and adjacent host rock and lower the relative humidity. Air corrosion rates are known to be lower than aqueous rates, particularly at low relative humidity, and current analyses predict relative humidities below 60 percent for hundreds to thousands of years (CRWMS M&O 1995; Buscheck et al. 1995). However, if percolation flux is determined to be in the higher part of the range discussed in Section 3.1, these relative humidities could be significantly larger. As noted in Section 3.1, after temperatures decrease, water that was mobilized while the temperatures were high may return to the waste package environment at rates that are less than, equal to, or greater than the current seepage rates. Thus, it is important to contain the waste throughout the thermal period to compensate for these uncertainties.

Engineered system enhancements that prolong the period of low humidity or delay liquid water contact could provide increased confidence in long-lived waste packages. The potential for use of ceramic coatings for the waste packages will be considered, as well as the use of a long-lived ceramic diversion

system in the emplacement drifts to eliminate the potential for seepage to contact the waste packages. Concerns about long-term durability related to rock falls could be addressed through use of a protective backfill.

The following hypotheses address the containment-related issues that need further resolution:

It is important to contain the waste throughout the thermal period to compensate for uncertainties.

5. Heat produced by emplaced waste will reduce relative humidity at the waste package surface.
6. Corrosion rates are very low at low relative humidity.
7. Double-walled waste packages will significantly increase containment times due to protection of the inner barrier by the outer barrier.
8. Engineered enhancements can extend the long period of containment of the inner barrier.

3.3 SLOW RATE OF RELEASE OF RADIONUCLIDES FROM THE WASTE FORM

Performance assessments show that the rate of release of radionuclides from the waste form is one of the key factors determining the peak dose rate. The strategy therefore focuses on mobilization of those radionuclides that potentially make a significant contribution to the peak dose rate. Many actinides that might be of concern are controlled by their solubility limits. Current assessments show the three main contributors to peak dose rate to be technetium-99, iodine-129, and neptunium-237, which are limited by the dissolution rate of spent fuel. Of much less concern is mobilization of radionuclides that are short-lived or that are not effectively transported after initial mobilization, as well as those that are mobilized in the gas phase and that travel as gases. The one gaseous exception may be iodine, which in recent performance assessments has been identified as possibly contributing significantly to peak dose rate because it may move away from waste packages as a gas early when temperatures are high, and then dissolve into the groundwater in the surrounding rock. This would require containment during the high temperature period.

Solubilities of radionuclides most important to performance have been measured or bounded. The approach in this strategy is to focus on verifying the dissolution rate of spent fuel, which is expected to control the dissolution rates of most of the more soluble radionuclides. Dissolution of vitrified high-level waste is not considered as important an issue because current evidence shows that the radionuclide release rates from vitrified waste are significantly lower than those of spent fuel for the critical radionuclides that contribute to calculated peak doses.

Solubilities of radionuclides most important to performance have been measured or bounded.

Using available data, dissolution rates of irradiated uranium dioxide were developed for a range of temperatures and water chemistries in the repository. Preliminary measurements of the dissolution rates of soluble species from spent fuel under unsaturated conditions suggest that the mobilization rates can be satisfactorily bounded for the purpose of performing total system analyses. Certain radionuclides could be mobilized more rapidly than the bounding uranium dioxide dissolution rate. This is true for soluble species that reside in the grain boundaries of the fuel pellets or that are subject to surface effects that lead

to preferential leaching. The most important of these is cesium, for which measurements show a leach rate that is no more than about twice the estimated spent fuel dissolution rate. However, cesium-137 has a 30-year half life, meaning that the quantities available will decay to insignificant levels in about 300 years.

There are a number of issues associated with the prediction of the radionuclide release rates from spent fuel. Dissolution of the radionuclides is a direct function of the surface area exposed and the amount of water that contacts the waste. The presence of cladding will significantly reduce the surface area of spent fuel available for release of radionuclides. An important issue regarding the dissolution rate of spent fuel is the potential for alteration to forms that dissolve more rapidly. Measurements show that the dissolution rate of unclad spent fuel that has been oxidized is significantly greater than that of unoxidized spent fuel, although the net increase in the dissolution rate in a repository setting is not known at this time. Oxidation of the spent fuel increases the surface area, releases radionuclides locked in the uranium dioxide grains, and alters some radionuclides to more soluble forms. If the waste is fully contained during the early period of high temperatures, this will limit the availability of oxygen and inhibit oxidation of the spent fuel. Therefore, whether the time of containment exceeds the period of high temperature of the waste becomes a key issue for mobilization rates.

The amount of water that contacts the waste can be limited by all of the barriers that limit water contact with the waste packages (Section 3.1). The waste can be further protected from water contact by the packages themselves, and within the packages, the defense waste canisters and the spent fuel cladding. Even if the engineered structures allow some water contact, the potential for advective flow can be limited by these structures and materials. Limiting the water contact rate directly limits mobilization rate.

As noted above, the concentration of many actinides is controlled by their solubility limit. Although initially released by the dissolution of the uranium dioxide matrix, most actinides partially precipitate because their solubility in groundwater is less than their concentration as released. Colloid formation could result in initial mobilization rates of some radionuclides, particularly the actinides, that are higher than those defined by their solubility limits. Evaluation of the potential for actinide transport to be enhanced by natural colloids or waste-package degradation colloids in groundwater is continuing.

Tests of hypotheses related to limited water and long containment will provide part of the basis for evaluating this attribute. Additional issues described above require that the following hypotheses be addressed:

9. Containment time will be sufficient to prevent oxidation of spent fuel during the thermal period.
10. The amount of water that contacts waste can be limited.
11. Release rate of soluble radionuclides will be controlled by slow dissolution of the waste form.
12. Release rate of actinides will be controlled by solubility limits rather than by colloidal stability.

3.4 CONCENTRATION REDUCTION DURING TRANSPORT

Radionuclides that are released from the waste form must migrate through the engineered barrier system and enter the unsaturated-zone flow system in the host rock in order to eventually reach the aquifers beneath the site. However, potential dose rates can be reduced during this transport. The dose rate depends directly on the concentration of radionuclides in the water. These concentrations change as the radionuclides migrate from the repository to the point of potential uptake by individuals using the water. In general, heterogeneities in the flow and transport properties cause dispersion; precipitation, matrix diffusion, and sorption cause depletion. Both of these processes cause reduction of the concentrations.

For those radionuclides with high solubility and limited potential for sorption (e.g., iodine, technetium), the design of the invert or a ceramic diversion system with backfill could be used in order to prevent advective flow. This could only work in an unsaturated site such as Yucca Mountain. Measurements of tuff gravels show that in cases where there is no advection, diffusion across the surface of partially saturated gravel fragments is very slow, with diffusion coefficients that are many orders of magnitude below those for saturated liquid diffusion. Experimental evidence shows that diffusion is a strong function of water content at low saturations (Conca 1990). At low water contents, transport occurs in thin films of water on the surface of the fragments, and mass transport, which depends on the film thickness, is much slower than in fully saturated media.

In the case of transport through engineered barriers, there are issues to resolve before diffusion or depletion can be demonstrated to be effective. The first and most important issue is the moisture condition (flow rates and saturations) in the engineered barriers. The seepage rate into the emplacement drifts must be bounded, and the associated saturations must be determined. Second, the flow and

transport characteristics of the engineered barriers need to be determined for these conditions. While considerable data exist for transport under saturated conditions, these observations need to be extended to unsaturated repository conditions. Third, although there is some information regarding the depletion potential of the engineered barriers, the tests have been for short periods and may not reflect equilibrium conditions. Additional information is needed to verify that laboratory-determined sorption and desorption effects result in depletion under repository conditions.

- Dispersive processes reduce concentrations of radionuclides during transport.
- Depletion refers to processes that lead to the effective removal of radionuclides as potential contributors to dose.

During transport through the natural barriers, dispersive mixing due to interactions between fracture and matrix flow and spatial heterogeneity may reduce radionuclide concentrations by as much as two orders of magnitude (CRWMS M&O 1995; Robinson et al. 1995; Robinson et al. 1997). Concentrations also can be reduced by depletion of radionuclides during transport by matrix diffusion and sorption. Sorption is a chemical bonding of the radionuclides to the minerals present in the rock fractures or matrix, whereas matrix diffusion involves movement of radionuclides from water in fractures into water in the adjacent rock matrix, driven by a physical or chemical gradient. If there is limited matrix diffusion, there can still be sorption on the walls of the fracture, but the depletion effect will be much smaller. Both of these processes together can reduce radionuclide concentrations in the groundwater of both the unsaturated and saturated zones. Understanding of these processes may be enhanced by the study of natural analogs such as the Nopal 1 uranium ore deposit at Peña Blanca in Chihuahua, Mexico. There, limited matrix diffusion has been observed in near-surface fractured tuffs in a wetter climate than Yucca Mountain. However, transport of oxidized uranium also has been very limited over very long (geologic) times (Murphy et al. 1997).

Because sorption is probably reversible for most of the poorly sorbing radionuclides, the net effect on transport is to delay the arrival of the radionuclides at the accessible environment. Under favorable circumstances in which the percolation flux is low, this delay can result in a reduction in the peak dose rate. Combining this with the effects of diffusion, dispersion, and radioactive decay, the concentrations of poorly sorbed radionuclides are expected to be reduced by several orders of magnitude after traveling through the natural barriers (Robinson et al. 1995; Robinson et al. 1997). For highly sorbing radionuclides, the concentrations are reduced by many more orders of magnitude. For some radionuclides,

removal can be considered permanent. In the case where the sorption reaction is found to be reversible, rates of desorption must be considered. It should be noted that when desorption occurs, the radionuclide then travels with the water and can be sorbed again. Generally, the rate of sorption is larger than the rate of desorption, resulting in a net mass removal of radionuclides from the downward moving water. If sorption occurs on migrating natural or introduced media such as colloid-sized mineral or iron-oxide particles, then delay and depletion can be greatly restricted, and the reductions noted above may not be realized. For example, there has been a field observation of the saturated zone migration of Pu from a weapons test location at the Nevada Test Site, apparently associated with colloid-sized mineral particles. The stability of these true radiocolloids under repository conditions has not yet been determined. Some information suggests that under repository conditions, these colloids would be unstable, or would occur in low enough concentrations so as not to provide a means to effectively transport radionuclides (Triay et al. 1995; Triay and Degueudre 1997).

If the amount of water seeping into the emplacement drifts and contacting the waste is small or mitigated by a diversion system, the radionuclide concentration arriving at the water table will be further reduced when this small flow is added to the larger flow

Dilution can reduce radionuclide concentrations and limit annual dose.

below the water table. This dilution depends upon the degree of mixing of the flow containing the radionuclides with the flow below the water table, and also upon the dispersion of the radionuclides during transport in the receiving flow. The strategy focuses on determining the ratio of the flow that may contact the waste to that in the receiving aquifer and the potential for advective mixing and dispersion of radionuclides in the aquifer.

Significant flow must occur in the saturated zone in order for the radionuclide-bearing flux that percolates to the water table to be diluted. Flow velocities have been estimated to be on the order of several meters per year on the basis of regional modeling (Czarnecki and Waddell 1984; Wilson et al. 1994; Luckey et al. 1996) and *Hydrologic Evaluation and Numerical Simulation of the Death Valley Regional-Groundwater Flow System, Nevada and California, Using Geoscientific Information Systems* (D'Agnese, F.A., Faunt, C.C., Turner, A.K., and Hill, M.C., in process. USGS/WRI 96-4300. Denver, Colorado: U.S. Geological Survey). The magnitude of mixing and dispersion also must be established because certain conditions have been noted to lead to persistence of contaminant plumes (Maqarin Study Group 1992; Gelhar et al. 1992). However, even persistent contaminant plumes may themselves be subject to significant dilution when mixed with other water in a producing well.

These questions must be addressed in an integrated evaluation. This evaluation requires that the following hypotheses regarding radionuclide transport characteristics be addressed:

13. Physical properties of both engineered and natural barriers will reduce radionuclide concentrations during transport.
14. Chemical properties of both the engineered and natural barriers will reduce radionuclide concentrations during transport.
15. Contaminants in the lower volume flow percolating down to the water table will be diluted by the higher volume flow in the aquifer.

4. EVALUATING DISRUPTIVE PROCESSES AND EVENTS

The strategy also must address the possibility that disruptions to the system potentially could release radionuclides directly to the human environment or otherwise adversely affect the characteristics of the system. Because the climate at Yucca Mountain is expected to change with time, climate change is included in nominal case for performance assessments and is therefore not treated as a disruptive process in this strategy (see Section 3.1). The following sections address tectonics and seismicity, and volcanism. Data already acquired for the site are sufficient to provide probabilities of tectonic activity and volcanic eruptions. Analyses are needed, however, to support assessments of the potential effects of such disruptions on the predicted doses to the public. Because Yucca Mountain is not regarded to be a future target for mineral resource exploration, no hypotheses related to human interference are identified in this strategy.

4.1 TECTONICS AND SEISMICITY

The strategy to address tectonic processes is based upon their likelihood and potential effects. Waste containment and isolation could be directly affected by movement on faults or ground motion related to earthquakes. The likelihood and magnitude of such fault movement or ground motion can be inferred from the geologic record of Quaternary movement on known faults at or near the site. The approach is to determine if potential movement on faults that extend through the repository horizon would have sufficient magnitude and frequency to adversely affect waste packages during the period they are relied upon to fully contain the waste.

Quaternary Period - the last two million years

Tertiary Period - The time from sixty-five million to two million years ago

Pliocene Epoch - the part of the Tertiary Period between about five million years ago and two million years ago

Estimated average Quaternary displacement rates on faults near the site, such as the Bow Ridge and the Solitario Canyon faults, range from .001 to .02 mm/year. Displacements per event range from a few centimeters to about a meter, with recurrence intervals of tens of thousands of years (Pezzopane 1995). Slip rates of this magnitude on a fault that might intersect the repository would be insufficient to transport waste to the surface, even over a period of hundreds of thousands of years. While fault displacements of this magnitude could possibly affect containment of waste packages in the vicinity of the fault, the long earthquake recurrence intervals indicate that adverse impacts on containment during the first several thousand years are highly unlikely. Fault displacements of lesser magnitudes may contribute to increased rockfalls or localized drift collapses, but these events are not expected to compromise containment or waste isolation performance.

Significant seismic effects on the flow system are not expected. The hydrologic flow system has been subjected to seismic activity throughout the Quaternary Period, and it is considered unlikely that future seismic activity will result in large changes to the regional groundwater flow system or the local unsaturated zone flow system at Yucca Mountain. Water table response to the 1992 Little Skull Mountain earthquake was small, and the water table

Transient increases in water table elevation due to seismic effects can be bounded at 20 to 30 m, which would have no adverse impact on performance.

returned to its ambient state within hours. The National Academy of Sciences (1992) examined available evidence for water table rise and concluded that seismic events could produce transient effects on the water table, but that the maximum transient rise in the past probably was less than 20 m. A more recent synthesis by the U.S. Geological Survey supports this conclusion (Paces et al. 1996). The proposed repository horizon is planned to be more than 150 m above the water table. Potential effects on the steep hydraulic gradient north and northwest of the site also have been examined. Modeling the effects of a "release" of the water associated with a rapid lowering of that steep gradient produces an increase in water table elevation of less than 30 m in the vicinity of the repository, which would not significantly affect waste isolation (Czarnecki 1989). This steep hydraulic gradient is thought to have persisted through numerous earthquakes in geologic history. Similarly, hydrologic characteristics of faults and fractures at Yucca Mountain represent the cumulative effect of numerous tectonic events. Future events are unlikely to significantly change those characteristics.

The hypotheses to be evaluated for tectonics and seismicity are:

16. 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.
17. 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.

4.2 VOLCANISM

Volcanism at the site could result in direct releases of radionuclides from the repository system as well as indirect effects due to fluids that might accompany the volcanic activity. The strategy is to infer from the geologic record the probability of a volcanic event within the repository boundaries and to estimate the consequences of such an event, were it to occur.

Because the possible entrainment of waste during an eruption is of most concern, the volume of magma and the change in eruptive volume through time is considered to be a useful indicator of potential effects. Crowe et al. (1995) summarized the work to date on past volcanic activity in the Yucca Mountain region. They concluded that the volumes of

erupted magma within the Yucca Mountain region have decreased exponentially since the Pliocene Epoch, although there may be a slight increase in frequency of eruptive events during the Quaternary Period.

Available information suggests that

volcanism has been drifting to the west for

the last three to four million years. In 1996, a probabilistic volcanic hazard analysis (CRWMS M&O 1996) was completed to assess the probability of disruption of the potential repository at Yucca Mountain by a volcanic event and to quantify the uncertainties associated with this assessment. The aggregate expected annual frequency of intersection of the potential repository by a volcanic event is 1.5×10^{-8} events/yr, with a 90-percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} . The mean value of 1.5×10^{-8} events/yr is consistent with values arrived at independently by previous research (Crowe et al. 1995).

The yearly probability of a volcanic eruption at the repository is about one in one hundred million.

Barnard et al. (1992) evaluated the consequences of direct effects of a basaltic magmatic intrusion into the repository. They evaluated releases from an event in which waste is entrained and subsequently exposed at the surface. In this evaluation, the calculated releases were small, on the order of the release limits

specified in the remanded standard that formerly applied to the Yucca Mountain site (40 CFR Part 191). Wilson et al. (1994) evaluated releases resulting from magmatic off-gassing and heat flow impacts and concluded that indirect effects due to volcanism are of little consequence to system performance.

The evaluations of consequences have so far considered only radionuclide releases. These assessments assumed that any waste on the surface was a release. No calculations of the consequences of volcanism on repository performance have been done that would be useful for comparison to a dose or risk standard. To adequately evaluate the radiological risk of volcanism to a population group near Yucca Mountain, a dose model must be applied to evaluate consequences, and consequences must then be normalized to the probability of a volcanic event at or near Yucca Mountain.

The hypothesis to be evaluated in this case is:

18. Volcanic events within the controlled area will be rare and the dose consequences of volcanism will be too small to significantly affect waste isolation.

4.3 HUMAN INTERFERENCE

The National Academy of Sciences (1995) considered human interference issues and concluded there is no scientific basis for projecting human activity thousands of years into the future. They turned their attention to whether analysis of the consequences of human interference could provide a useful basis for evaluating a proposed repository site and design. They concluded that the calculations of consequences would provide useful information about how well a repository might perform after an intrusion occurs.

While it is true that there is no scientific basis for projecting human activity thousands of years into the future, the continued existence and profitability of resource exploration companies depends upon the ability to assess whether sites are likely candidates for future resource development. Therefore, it is assumed that the approaches used by such companies provide a useful indicator of how explorations and assessments would be conducted, at least in the near future. While no data or analyses can guarantee that human intrusion will not occur in the future, or even predict its probability, the approach in this case is to determine if Yucca Mountain is likely to be of interest for resource exploration or development in the foreseeable future.

The Yucca Mountain site and region have been assessed with regard to resource potential (DOE 1986; Castor et al. 1989; Younker et al. 1992). None of these evaluations have suggested that the site is a likely target for future exploration. Given these resource assessments, no hypotheses regarding human interference are proposed.

4.4 NUCLEAR CRITICALITY

The presence of fissile radionuclides such as uranium-235 and plutonium-239 in the radioactive waste means that an evaluation must be made regarding whether a sustained neutron chain reaction (a criticality event) could occur. The results of a criticality event involve the local generation of heat and an increase in the fission product inventory. No realistic scenario has been developed through which such an event could significantly affect either containment or waste isolation. The strategy to address

No realistic scenario has been developed by which a nuclear criticality event could significantly affect waste isolation.

nuclear criticality focuses on the probabilities of conditions needed to support the criticality reaction, and the consequences of such an event.

Analyses to date indicate that the probability of criticality under dry conditions is very low for commercial spent nuclear fuel disposal. If water is not available to transport radionuclides, the fissile radionuclides would remain in the waste packages, and there is an insufficient quantity of plutonium-239 or uranium-235 in the commercial spent fuel waste packages to support a sustained reaction without water moderation (Sanchez 1995). Even if water is available, the water would need to first preferentially dissolve and remove the neutron absorbing materials in the waste package, and then fill the waste package to provide a moderator.

Likewise, the probability of criticality if fissile radionuclides are transported outside of the waste package is estimated to be low. A criticality event is considered unlikely in the near-field, both because the conditions required to concentrate fissile materials are unlikely, and sufficient water to moderate a reaction is lacking. A far-field criticality event requires preferential localized deposition of fissile material from multiple waste packages along transport pathways in the host rock. The formation of a critical configuration of fissile material in the far-field also requires adequate moderation and mechanisms for removing the neutron absorbing isotopes intrinsic to the spent fuel. Thus, the probability of a far-field criticality event is also very low.

No hypothesis is defined for criticality because the information about the characteristics of the waste form, the corrosion of waste packages, and the dissolution and transport of fissile radionuclides and neutron absorbers is available through evaluation of other hypotheses. Information needed to evaluate transport of radionuclides through the rock units underlying the repository will be obtained to evaluate the hypotheses related to seepage, containment, mobilization, and transport. This information can be used to determine the likely environments and geometric configurations of the mobilized radionuclides to establish the probability of criticality, and if necessary, the consequences within the context of total system performance.

5. IMPLICATIONS OF THE UPDATED STRATEGY

Improved site understanding and maturation of design concepts for the engineered system provide the basis for more refined performance assessments. Using recent performance assessments, the key attributes of the natural and engineered systems have been identified. For each attribute, the major questions that remain to be answered have been stated as testable hypotheses. How the percolation flux at repository depth is reflected as seepage into the emplacement drifts, and how much of that seepage contacts the waste packages continues to be the key system attribute impacting performance. If the water contacting the waste packages is as small as current interpretations suggest, and remains small through future climate and thermally induced changes, waste packages will corrode very slowly and waste will be contained in them for thousands of years. As waste packages eventually fail, multiple lines of defense such as solubility limits of the radionuclides, dispersion and depletion during transport, and dilution are expected to result in acceptably low annual doses.

Understanding the key attributes affecting waste containment and isolation also will allow evaluation of improvements that could enhance total system performance. In particular, evaluations of the hypotheses may have implications for the design of the waste packages, the value of backfill and other engineered barriers, and the usefulness of controlling the density of heat-generating waste in the repository.

Identification of the key attributes and definition of the hypotheses in this strategy enables focusing of this testing and analysis program on the key remaining questions related to repository performance. The

information sources most useful for testing the hypotheses are summarized in Table 1. The tests and analyses include numerical modeling of processes at detailed levels and as a total system, laboratory testing to constrain key parameters, observations and *in situ* tests in the Exploratory Studies Facility and other underground locations, and other field and natural analog tests. Boxes in Table 1 containing a single check mark represent sources where additional information will be needed to evaluate the hypothesis. Two check marks identify areas where significant information exists but additional testing or analyses are expected to improve and confirm current understanding. Three check marks indicate areas where testing or analyses to support the current phase of the program are essentially complete, although performance confirmation requirements could lead to future additional work. Ongoing planning of the scientific and engineering programs will lead to a more detailed delineation of remaining testing and analysis needed to evaluate the hypotheses. Existing data, combined with the results of additional tests and analyses, will be compiled, interpreted and synthesized to provide the parameters and models for evaluations of waste containment and isolation that become more comprehensive with time.

Table 1. Information Sources for Testing Hypotheses

Attribute	Hypotheses to be Evaluated	Type of Testing or Analysis			
		Numerical Modeling	Laboratory Testing	ESF/In situ Observations and Testing	Surface-Based Field Testing
Limited Water Contacting Waste Packages	1. Percolation flux at repository depth can be bounded	✓✓	✓✓	✓✓	✓✓
	2. Seepage into drifts will be a fraction of percolation flux	✓	✓✓	✓✓	N/A
	3. Thermally induced seepage can be bounded	✓✓	✓✓	✓✓	N/A
	4. Seepage that contacts waste packages can be limited	✓	✓	✓	N/A
Long Waste Package Lifetime	5. Heat reduces relative humidity at waste package surface	✓✓	N/A	✓	N/A
	6. Slow corrosion at low relative humidity	✓✓	✓	✓	N/A
	7. Protection of inner barrier by the outer barrier	✓✓	✓✓	N/A	N/A
	8. Engineered enhancements can extend the long period of containment of the inner barrier	✓	✓	✓	N/A
Slow Rate of Radionuclide Release	9. Containment time sufficient to prevent oxidation of spent fuel	✓✓	✓✓	N/A	N/A
	10. Water that contacts waste can be limited	✓	✓	N/A	N/A
	11. Release rate of soluble radionuclides controlled by slow waste form dissolution	✓✓	✓✓	N/A	N/A
	12. Release rate of actinides controlled by solubility limits rather than colloidal stability	✓✓	✓✓	N/A	N/A

Attribute	Hypotheses to be Evaluated	Type of Testing or Analysis			
		Numerical Modeling	Laboratory Testing	ESF/In situ Observations and Testing	Surface-Based Field Testing
Concentration Reduction of Radionuclides During Transport	13. Physical properties of barriers reduce concentrations during transport	✓✓	✓✓	✓	✓✓
	14. Chemical properties of barriers reduce concentrations during transport	✓✓	✓✓✓	✓	✓✓
	15. Lower volume flow in unsaturated zone will be diluted by higher volume flow in the saturated zone	✓✓	N/A	N/A	✓✓
Disruptive Processes & Events					
Tectonics & Seismicity	16. Fault displacement impacts not significant	✓✓	N/A	✓✓	✓✓✓
	17. Minimal ground motion impacts	✓✓	N/A	✓✓	✓✓✓
Volcanism	18. Consequences of volcanism limited	✓✓✓	N/A	N/A	✓✓✓

6. REFERENCES

6.1 CITED DOCUMENTS

- Barnard, R.W. and Dockery, H.A., eds. 1991. "Technical Summary of the Performance Assessment Calculational Exercises for 1990 (PACE-1990)." Volume 1: *Nominal Configuration Hydrogeologic Parameters and Calculational Results*. SAND90-272. Albuquerque, New Mexico: Sandia National Laboratories.
- Barnard, R.W., Wilson, M.L., Dockery, H.A., Gauthier, J.H., Kaplan, P.G., Eaton, R.R., Bingham, F.W., and Robey, T.H. 1992. *TSPA-1991: An Initial Total-System Performance Assessment for Yucca Mountain*. SAND91-2795. Albuquerque, New Mexico: Sandia National Laboratories.
- Bodvarsson, G.S., Bandurraga, T.M., and Wu, Y.S. 1997. *The Site-scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment*. YMP Milestone Report SP24BM3. LBNL Report LBNL-40376. Berkeley, California: Lawrence Berkeley National Laboratory.
- Buscheck, T.A. 1996. "Hydrothermal Modeling," Chapter 1 in Wilder, D.G., Scientific Ed., *Near-Field and Altered-Zone Environment Report*. Vol. II. UCRL-LR-124998. Berkeley, California: Lawrence Livermore National Laboratory.
- Buscheck, T.A., Nitao, J.J., and Ramspott, L.D. 1995. Localized Dry-Out: An Approach for Managing the Thermal-Hydrological Effects of Decay Heat at Yucca Mountain. *Materials Research Society XLX International Symposium on the Scientific Basis for Nuclear Waste Management*. Boston, Massachusetts: Materials Research Society.
- Castor, S.B., Feldman, S.C., and Tingley, J.V. 1989. *Mineral Evaluation of the Yucca Mountain Addition, Nye County, Nevada*. Open File Report OFR90-4. Reno, Nevada: Nevada Bureau of Mines and Geology, University of Nevada, Reno.
- Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) 1995. *Total System Performance Assessment-1995: An Evaluation of the Potential Yucca Mountain Repository*. B00000000-01717-2200-00136 REV 00. Las Vegas, Nevada: Civilian Radioactive Waste Management System Management and Operating Contractor.
- CRWMS M&O 1996. *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada*. BA00000000-01717-2200-00082 REV 00. Las Vegas, Nevada: Civilian Radioactive Waste Management System Management and Operating Contractor.
- Conca, J.L. 1990. "Transport in Unsaturated Flow Systems Using Centrifuge Techniques." *Proceedings of the DOE/Yucca Mountain Site Characterization Project Radionuclide Adsorption Workshop*. September 11-12, 1990. LA-12325-C. Los Alamos, New Mexico: Los Alamos National Laboratory.
- Crowe, B., Perry, F., Geissman, J., McFadden, L., Wells, S., Murrell, M., Poths, J., Valentine, G.A., Bowker, L., and Finnegan, K. 1995. *Status of Volcanism Studies for the Yucca Mountain Site Characterization Project*. LA-12908-MS. Los Alamos, New Mexico: Los Alamos National Laboratory.
- Czarnecki, J.B. and Waddell, R.K. 1984. *Finite-Element Simulation of Ground-Water Flow in the Vicinity of Yucca Mountain, Nevada-California*. USGS/WRI 84-4349. Denver, Colorado: U.S. Geological Survey.
- Czarnecki, J.B. 1989. "Preliminary Simulations Related to a Large Horizontal Hydraulic Gradient at the North End of Yucca Mountain, Nevada." *EOS*, 70 [15], 321. Washington, D.C.: American Geophysical Union.

DOE (U.S. Department of Energy) 1986. *Environmental Assessment, Yucca Mountain Site, Nevada Research and Development Area, Nevada*. DOE/RW-0073. Washington, D.C.: Office of Civilian Radioactive Waste Management.

DOE 1988. *Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada*. DOE/RW-0199. Washington, D.C.: Office of Civilian Radioactive Waste Management.

Eslinger, P.W., Doremus, L.A., Engel, D.W., Miley, T.B., Murphy, M.T., Nichols, W.E., White, M.D., Langford, D.W., and Ouder Kirk, S.J. 1993. *Preliminary Total-System Analysis of a Potential High-Level Nuclear Waste Repository at Yucca Mountain*. PNL-8444. Richland, Washington: Pacific Northwest Laboratory.

Fabryka-Martin, J.T., Flint, A.L., Sweetkind, D.S., Wolfsberg, A.V., Levy, S.S., Roemer, G.J.C., Roach, J.L., Wolfsberg L.E., and Duff, M.C. 1997. *Evaluation of Flow and Transport Models of Yucca Mountain Based on C1-36 Studies*. Yucca Mountain Project Milestone Report SP2224M3. LA-CST-TIP-97-010. Los Alamos, New Mexico: Los Alamos National Laboratory.

Gelhar, L.B., Welty, G., and Rehfeldt, R. 1992. "A Critical Review of Data on Field-Scale Dispersion in Aquifers." *Water Resources Research*. Vol. 28. pp. 1955-1974. Washington, D.C.: American Geophysical Union.

Luckey, R.R., Tucci, P., Faunt, C.C., Ervin, E.M., Steinkampf, W.C., D'Agnese, F.A., and Patterson, G.L. 1996. *Status of Understanding of the Saturated-Zone Ground-Water Flow System at Yucca Mountain, Nevada, as of 1995*. USGS/WRI 96-4077. Denver, Colorado: U.S. Geological Survey.

Maqarin Study Group 1992. *Natural Analog Study of Maqarin Hyper-Alkaline Groundwaters*. Technical Report 91-10. December 1992. Stockholm, Sweden: National Cooperative for the Disposal of Radioactive Waste (NAGRA).

McGuire, R.K., Bullen, D.B., Cook, N., Coppersmith, K.J., Kemeny, J., Long, A., Pearson Jr., F.J., Schwartz, F., Sheridan, M., and Youngs, R.R. 1990. *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluations*. EPRI NP-7057. Palo Alto, California: Electric Power Research Institute.

Montazer, P. and Wilson, W.E. 1984. *Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada*. USGS/WRI 84-4345. Denver, Colorado: U.S. Geological Survey.

National Academy of Sciences (NAS) 1992. *Ground Water at Yucca Mountain - How High Can it Rise? Final Report of the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain*. Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources, National Research Council. Washington, D.C.: National Academy Press.

NAS 1995. *Technical Basis for Yucca Mountain Standard*. Board of Radioactive Waste Management. National Research Council of the National Academy of Sciences. Washington, D.C.: National Academy Press.

Paces, J.B., Forester, R.M., Whelan, J.F., Mahan, S.A., Quade, J., Neymark, L.A., and Kwak, L. 1996. *Synthesis of Groundwater Discharge Deposits near Yucca Mountain*. U.S. Geological Survey Milestone Report 3GQH671M. Denver, Colorado: U.S. Geological Survey.

Pezzopane, S.K. 1995. *Preliminary Table of Characteristics of Known and Suspected Quaternary Faults in the Yucca Mountain Area*. U.S. Geological Survey Administrative Report, prepared for U.S. Department of Energy. Denver, Colorado: U.S. Geological Survey.

Robinson, B.A., Wolfsberg, A.V., Zyvoloski, G.A., and Gable, C.W. 1995. *An Unsaturated Zone Flow and Transport Model of Yucca Mountain*. YMP Milestone Number 3468. Los Alamos, New Mexico: Los Alamos National Laboratory.

Robinson, B.A., Wolfsberg, A.V., Viswanathan, H.S., Bussod, G.S., Gable, C.W., and Meijer, A. 1997. *The Site-Scale Unsaturated Zone Transport Model of Yucca Mountain*. YMP Milestone Number SP25BM3. Los Alamos, New Mexico: Los Alamos National Laboratory.

Sanchez, R. 1995. *Criticality Characteristics of Mixtures of Plutonium, Silicon Dioxide, Nevada Tuff, and Water*. LA-UR-95-2130. Los Alamos, New Mexico: Los Alamos National Laboratory.

Triay, I., Degueudre, C., Wistrom, A., Cotter, C., and Lemons, W. 1995. *Progress Report on Colloid-Facilitated Transport at Yucca Mountain*. YMP Milestone Number 3383. LA-12959-MS. Los Alamos, New Mexico: Los Alamos National Laboratory.

Triay, I., and Degueudre, C. 1997. *Concentrations of Colloids in Yucca Mountain Waters*. YMP Milestone Report SP341LM4. Los Alamos, New Mexico: Los Alamos National Laboratory.

Wilson, M.L., Gauthier, J.H., Barnard, R.W., Barr, G.E., Dockery, H.A., Dunn, E., Eaton, R.R., Guerin, D.C., Lu, N., Martinez, M.J., Nilson, R., Rautman, C.A., Robey, T.H., Ross, B., Ryder, E.E., Schenker, A.R., Shannon, S.A., Skinner, L.H., Halsey, W.G., Gansemer, J.D., Lewis, L.V., Lamont, A.D., Triay, I.R., Meijer, A., and Morris, D.E. 1994. *Total System Performance Assessment for Yucca Mountain — SNL Second Iteration (TSPA-1993)*. SAND93-2675. Albuquerque, New Mexico: Sandia National Laboratories.

Yunker, J., Andrews, W., Fasano, G., Herrington, C., Mattson, S., Murray, R., Ballou, L., Revelli, M., DuCharme, A., Shephard, L., Dudley, W., Hoxie, D., Herbst, R., Patera, E., Judd, B., Docka, J., and Rickertsen, L. 1992. *Report of the Early Site Suitability Evaluation of the Potential Repository Site at Yucca Mountain, Nevada*. SAIC-91-8000. Las Vegas, Nevada: Science Applications International Corporation.

6.2 REGULATIONS, PUBLIC LAW

10 CFR 60, *Disposal of High-level Radioactive Wastes in Geologic Repositories*. Washington, D.C.: Nuclear Regulatory Commission.

40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-level and Transuranic Radioactive Wastes*. Washington, D.C.: Environmental Protection Agency.

Energy Policy Act of 1992, Public Law 102-486.

APPENDIX A

CHANGES FROM REVISION 0 TO REVISION 1

This document was originally drafted as *Highlights of the U.S. Department of Energy's Updated Waste Containment and Isolation Strategy, Yucca Mountain Site, Nevada*, YMP/96-01, Revision 0, September 1996. It was transmitted as a draft by the DOE to the Nuclear Regulatory Commission and the Nuclear Waste Technical Review Board in July 1996. Although the original draft status might warrant use of Revision 0 for the present document, it was decided to use Revision 1, and to prepare this appendix summarizing the similarities and differences between the two documents.

Comparison of the Table of Contents will show that the basic outline has not changed, except that a Summary has been added to the present document. The concept of identifying key attributes of the repository system and important testable hypotheses associated with each key attribute remains, although the statement of the attributes and hypotheses has been revised as the concept has matured. The differences are summarized in Table A-1.

During the more than a year between preparation of Revision 0 and Revision 1, new site data have become available, and refinements have continued in assessment of the site. Among the more important site information has been evidence that the average percolation flux at the repository horizon may be greater than formerly concluded (formerly 1 mm per year or less, now on the order of 5 to 10 mm per year); that in localized zones associated with major fractures, water may have traveled from the surface to repository level in less than 50 years; and that there is field evidence at NTS of the migration of plutonium at very low concentrations in association with natural colloid-sized mineral particles. This information has clarified that what is important is how much of the water entering the drift actually contacts waste packages and the waste itself. Revision 1 therefore has added specific hypotheses related to engineering enhancements that might restrict such contact.

As shown in Table A-1, the key attributes have been restated and the number has been reduced from five to four, although the underlying concepts have not changed. The statement of the key attributes is now outcome-based rather than process-oriented, and given as descriptive phrases rather than one or two key words. For example, Seepage (a single word describing a process) is now stated as Limited Water Contacting Waste Packages (a phrase describing a desired outcome). This change also reflects the realization that the key attribute is not how much seepage enters the drifts, but how much water contacts the waste packages. Containment was changed to Long Waste Package Lifetime. Radionuclide Mobilization is now stated as Slow Rate of Radionuclide Release. Radionuclide Transport and Dilution have been combined as Concentration Reduction of Radionuclides During Transport, reducing the number of key attributes from five to four.

No hypotheses have been deleted, although some have been combined. New hypotheses have been added, and some hypotheses have been restated.

Under the Limited Water Contacting Waste Packages attribute of Revision 1, Hypotheses 1 and 5 of Revision 0 were combined as Hypothesis 1 of Revision 1, which is the specific ambient site information required by performance assessment. Hypotheses 2 and 3 of Revision 0 have been combined into Hypothesis 2 of Revision 1, which states the desired outcome rather than the previous state descriptions of the environment. Hypothesis 4 of Revision 0 is restated as Hypothesis 3 of Revision 1 to address seepage rather than flux, paralleling Hypothesis 2 of Revision 1. Hypothesis 4 in Revision 1 has been added to reflect the shift of emphasis from seepage into the drift to how much water contacts the waste packages.

Under the Long Waste Package Lifetime attribute, Hypotheses 6, 7, and 8 of Revision 0 have been restated as 5, 6, and 7 of Revision 1 and a new Hypothesis 8 added to reflect enhancements being considered to support containment.

Under the Slow Rate of Radionuclide Release attribute, Hypothesis 9 of Revision 0 was a single hypothesis that essentially stated the attribute. In Revision 1, it has been divided into hypotheses (9, 10, 11, and 12) that must be demonstrated to support the attribute. Hypothesis 9 in Revision 1 was formerly an unstated outcome of Containment, and Hypothesis 10 was formerly an unstated outcome of low Seepage. Hypothesis 12 explicitly addresses colloidal stability (therefore migration).

Under the Concentration Reduction of Radionuclides During Transport attribute, Hypothesis 10 of Revision 0 has been divided into Hypothesis 13 (dispersion) and 14 (depletion) in Revision 1. Hypotheses 11 and 12 of Revision 0 have been combined into Hypothesis 15 in Revision 1. Now depletion, dispersion, and dilution each have a separate hypothesis.

The hypotheses related to Disruptive Processes and Events have not changed.

Revision 1 gives the interim performance measure and goal established by the DOE prior to receiving final regulatory guidance. It also clarifies the difference between this strategy and the safety case that will be established for VA and the LA. It includes a brief discussion of multiple barriers, defense in depth, and margin of safety. The entire document has been revised, in some parts substantially and in others very little.

Table A-1. Comparison of Attributes and Hypotheses Between Revision 0 and Revision 1

REVISION 0		REVISION 1	
Attribute	Hypotheses to be Evaluated	Attribute	Hypotheses to be Evaluated
Seepage	1. Low percolation flux at repository depth	Limited Water Contacting Waste Packages	1. Percolation flux at repository depth can be bounded
	2. Limited fracture flow at repository depth		2. Seepage into drifts will be a fraction of percolation flux
	3. Capillary retention reduces seepage into drifts		3. Thermally induced seepage can be bounded
	4. Thermally induced flux can be bounded		4. Seepage that contacts waste packages can be limited
	5. Effects of climate change can be bounded		
Containment	6. Low humidity at waste package surface	Long Waste Package Lifetime	5. Heat reduces relative humidity at waste package surface
	7. Slow corrosion at low humidity		6. Slow corrosion at low relative humidity
	8. Galvanic protection of inner barrier		7. Protection of inner barrier by the outer barrier
			8. Engineered enhancements can extend the long period of containment of the inner barrier
Radionuclide Mobilization	9. Low mobilization rates from waste forms	Slow Rate of Radionuclide Release	9. Containment time sufficient to prevent oxidation of spent fuel
			10. Water that contacts waste can be limited
			11. Release rate of soluble radionuclides controlled by slow waste form dissolution
			12. Release rate of actinides controlled by solubility limits rather than colloidal stability

REVISION 0		REVISION 1	
Attribute	Hypotheses to be Evaluated	Attribute	Hypotheses to be Evaluated
Radionuclide Transport	10. Radionuclide concentrations reduced by depletion and dispersion	Concentration Reduction of Radionuclides During Transport	13. Physical properties of barriers reduce concentrations during transport
Dilution	11. Flux in saturated zone >flow contacting waste		14. Chemical properties of barriers reduce concentrations during transport
	12. Strong mixing occurs in saturated zone		15. Lower volume flow in unsaturated zone will be diluted by higher volume flow in the saturated zone
Disruptive Processes & Events			
Tectonics & Seismicity	13. Fault displacement impacts not significant	Tectonics & Seismicity	16. Fault displacement impacts not significant
	14. Minimal ground motion impacts		17. Minimal ground motion impacts
Volcanism	15. Consequences of volcanism limited	Volcanism	18. Consequences of volcanism limited