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Status Report: Potential for Long-Term Isolation by the Waste Isolation Pilot Plant Disposal System

Sharla G. Bertram-Howery, Peter N. Swift

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STATUS REPORT: POTENTIAL FOR LONG-TERM ISOLATION BY THE WASTE ISOLATION PILOT PLANT DISPOSAL SYSTEM

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ABSTRACT

The U.S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) must comply with EPA regulation 40 CFR Part 191, Subpart B, which sets environmental standards for radioactive waste disposal. The regulation, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (hereafter referred to as the Standard), was vacated in 1987 by a Federal Court of Appeals and is undergoing revision. By agreement with the State of New Mexico, the WIPP Project is evaluating compliance with the Standard as promulgated in 1985 until a new regulation is available.

This report summarizes the early-1990 status of Sandia National Laboratories' (SNL) understanding of the Project's ability to achieve compliance. The report reviews the qualitative and quantitative requirements for compliance, and identifies unknowns complicating performance assessment. It discusses in relatively nontechnical terms the approaches to resolving those unknowns, and concludes that SNL has reasonable confidence that compliance is achievable with the Standard as first promulgated. This report is not a formal evaluation of compliance: available data and models are insufficient for a full-scale assessment and 40 CFR Part 191 has not been reissued following remand. The first preliminary performance-assessment report for the WIPP will be completed in December 1990.

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The WIPP Performance Assessment Peer Review Panel
SNL Waste Management Technology Department
DOE Engineering Alternatives Task Force
DOE WIPP Integration Committee
DOE WIPP Project Office
DOE Albuquerque Operations Office
DOE WIPP Task Force
DOE Environmental Guidance Division
DOE Office of Environmental Restoration and Waste Management

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FOREWORD

This report was written to provide the U.S. Department of Energy a summary of the WIPP Project's status and the disposal system's potential for long-term isolation as measured by the Environmental Protection Agency's (EPA's) environmental standards for radioactive waste disposal (40 CFR Part 191). Receiving waste for planned experiments at the WIPP depends in part on this information. Performance assessment is currently based on the 1985 version of the Standard that was vacated and remanded to the EPA by a Federal Court of Appeals in 1987.

Our purpose is to show that the WIPP Project will ultimately demonstrate compliance with EPA's standards, even though we cannot assure with the necessary degree of completeness that we comply today. This report will help decision makers, reviewers, and the public understand where the Project is and what activities are underway to assure that the Project can show compliance with the Standard when it is repromulgated.

The three avenues by which the Project proposes to achieve compliance will all be explored concurrently, but with different thrusts. First, we find in studies Sandia National Laboratories (SNL) has done to date that because of the large uncertainty in many of the data parameters, we have to use data distributions based upon incomplete knowledge. This results in two preliminary conclusions: (1) the WIPP disposal system is excellent provided it is undisturbed by human intrusion, and (2) pessimistic assumptions about human intrusion and the data for modeling it produce some results that are not within the limits imposed by the EPA's Containment Requirements. One avenue, therefore, is to work on those data uncertainties and see to what extent they can be reduced. That is the primary purpose of activities described in the *WIPP Test Phase Plan: Performance Assessment* (DOE/WIPP 89-011, April 1990). The Test Phase was conceived and planned to reduce the ranges of uncertainty now conservatively assumed for many of the parameters. This is true of the experiments with waste and a host of other activities: gas generation, mitigation, and dispersal tests; plugging and sealing tests; room-model development; and two-phase liquid/gas flow studies. While we believe many of these improvements in knowledge likely will decrease the pessimism in the assumptions, we cannot prejudge the results and say that all the changes from increased knowledge will be towards compliance or sufficient to bring the disposal system into full compliance. For this reason, we are working concurrently along two other avenues.

The second avenue is to examine the regulatory requirement for quantifying human intrusion. We are asking expert panels to judge the probability of intrusion and to predict the effectiveness and durability of passive institutional controls. Experts on these panels will all be from outside the DOE waste-management program. Expert panels and in-house research will examine how well future boreholes could be plugged, considering information transfer to future societies via markers and records, along with salt creep behavior, standard drilling-industry practice, and so on. We are examining all the

requirements of the regulation, one of the more important ones being the human intrusion guidance. The Project will provide information to the EPA as they revise and repromulgate the Standard. We will be pursuing this approach while collecting additional data to improve our knowledge. Again, at this stage, we cannot predict the results or how they will impact the performance assessment; therefore, the Project is looking concurrently at still a third avenue, engineered alternatives.

The Project has convened a multidisciplinary panel to identify alternatives for waste form and repository design that should improve the ability of the WIPP to reduce potential releases. This panel will assess the cost and other impacts, such as occupational exposure to radiation, of these alternatives. Because we do not know to what extent, if any, such alternatives will ultimately be required, the Project is looking at a range of alternatives and will quantify the most appropriate ones so that the DOE could apply them with sufficient confidence in their function if they are shown to be necessary.

As information is developed from the test phase experiments, from expert panels, and from evaluation of alternative waste forms, it will be incorporated into the performance-assessment calculations. The first suite of calculations, which may be considered to be a preliminary performance assessment for WIPP, will be reported in December 1990 based upon data available in the summer of 1990. This evaluation will be conducted with all scenarios believed to be relevant, the most current models and data, preliminary consideration of gas build-up in the waste rooms, and extension of the performance assessment to consideration of safety. In particular, such aspects as climatic variation, scenario probability, preliminary two-phase flow treatment of gas in the repository, dual-porosity transport in the aquifers, and more detailed consideration of human intrusion will be incorporated. Performance assessments will be updated semiannually and reported annually.

Some readers may object that it is illogical for this report to conclude there is reasonable confidence that compliance is achievable without demonstrating compliance. We believe that the conclusion is logical and that it must be made at this time. Predictions of feasibility are an essential part of research and development projects, and because they must be available to those who make the decisions to allocate resources, such predictions invariably must anticipate fulfillment of the project goals. NASA was able to predict the achievability of a manned moon landing years before they could demonstrate it. Had realistic predictions of ultimate success not been available in advance, the task might never have been undertaken. Similarly, we can now predict with reasonable confidence that regulatory compliance can be achieved for the WIPP and it is therefore appropriate to continue the research and testing needed to insure the safe disposal of transuranic radioactive waste.

Wendell D. Weart, Manager
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EXECUTIVE SUMMARY

Before the Waste Isolation Pilot Plant (WIPP) may begin service as the United States' first repository for the permanent disposal of transuranic radioactive waste, the Department of Energy (DOE) must establish compliance with applicable environmental and safety regulations. This report addresses one major regulation, the United States Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (40 CFR Part 191 in U.S. EPA, 1985), hereafter referred to as the Standard. The report does not address compliance with other regulations.

This report summarizes Sandia National Laboratories' (SNL) early-1990 understanding of the WIPP Project's ability to comply with the long-term performance requirements set by Subpart B of the Standard. The report also reviews the current understanding of questions critically affecting compliance. Options available to assure that radionuclide releases will remain within regulatory limits are outlined, and the report concludes that SNL has reasonable confidence that compliance is achievable. Regulatory compliance cannot be formally evaluated at present because the Standard has not been reissued since it was vacated in 1987 by a Federal Court of Appeals. Available data and models are insufficient for complete simulations of repository performance; however, current simulations are adequate for programmatic guidance. Research in progress will increase confidence in predictions of performance, and if necessary, design modifications could assure regulatory compliance. Effective and feasible options for improving repository performance are being researched so that they will be available if needed, and the relative costs and benefits of these options are being assessed. The major question remaining is not whether the WIPP can comply with the Standard, but rather how it should comply.

Performance assessment and experimental research programs for the WIPP Project are conducted by SNL, the Scientific Advisor for the Project. Potential modifications to the present design of the disposal system are being evaluated by the Engineered Alternatives Task Force (EATF), assembled by International Technology Corporation for Westinghouse Electric Corporation, the Management and Operating Contractor for the Project.

Compliance with the Individual Protection Requirements, applicable to undisturbed performance, appears certain for the repository as presently designed. Preliminary calculations indicate that if the repository remains undisturbed,

no radionuclides whatsoever will be released during the period of regulatory control. Expected undisturbed performance satisfies regulatory limits by orders of magnitude.

Currently, compliance with the Ground Water Protection Requirements is not relevant because no "special source of ground water," as defined by the Standard, exists at the site. The brines present in small quantities in the Salado Formation that contains the repository and in larger quantities in the overlying units are highly saline, and none is a source of drinking water.

Preliminary calculations also suggest compliance with the Containment Requirements can be achieved for the repository as currently designed. The compliance evaluation is dominated by inadvertent human intrusion. Calculations suggest that releases following intrusion by an exploratory borehole possibly could exceed regulatory limits if several extremely unfavorable circumstances coincide. Those circumstances have been assumed for the most pessimistic simulations. Performance-assessment work has therefore concentrated on better simulating consequences of human intrusion to determine effects on compliance and to determine what, if any, modifications might be needed to assure compliance.

The limits set by the Containment Requirements of the Standard are defined probabilistically. One limit is specified for releases resulting from events or processes with a probability of greater than 1 chance in 10 during the 10,000 years following decommissioning of the repository. A second, higher limit is specified for releases that might result from less-likely circumstances with probabilities of occurrence between 1 in 10 and 1 in 1000. Radioactive releases resulting from circumstances with less than 1 chance in 1,000 during the 10,000-year period are not limited.

The EPA's intent was to link regulatory limits to the probability of release, allowing compliance to be judged on the probable circumstances of the next 10,000 years, rather than on the worst conceivable circumstances. As a consequence of this approach, performance assessments used to evaluate compliance must be probabilistic. The SNL performance-assessment team must determine probabilities for future events, including human intrusion, and must assign probabilistic distribution functions to all uncertain or variable parameters that may affect long-term performance.

Multiple simulations using a complex modeling system and an extensive database will be needed to generate probabilistic predictions. Because some model components and portions of the database are still incomplete, predictions to date have been based in part on conservative assumptions. Available

predictions are therefore believed to be pessimistic: actual performance is highly unlikely to be worse than predicted and may be substantially better. An expanded database and improved models will permit more accurate predictions that may show less-pessimistic estimates of radionuclide releases.

All performance assessments to date have pessimistically assumed that any plugs installed in an intruding borehole will deteriorate to be no more effective than sand and rubble. This report presents analyses to show that if future drillers recognize the implications of their mistake and plug the borehole as effectively as the repository will be sealed upon decommissioning, long-term radionuclide releases should not occur. In this case, even with the current design for the repository and waste, the WIPP will remain in compliance with Subpart B of the Standard.

All performance assessments to date have also assumed that intrusion will occur. The possibility cannot be ruled out, but research is in progress to design a passive marker system that will significantly reduce the probability of intrusion. Because future human actions cannot be quantified by conventional research methods, the potential effectiveness of markers will be evaluated by a panel of experts. Qualitative judgment will determine the appropriate probability of intrusion.

Uncertainties about the consequences of gas generation within the repository further complicate performance simulations. Available evidence suggests that gas generation and a rise in pressure will not degrade undisturbed performance. Significant radionuclide transport requires a liquid medium, and increased gas pressures could keep the repository too dry for transport to occur. Gas generation has the potential, therefore, to enhance undisturbed performance. If intruders penetrate a pressurized repository, however, radionuclide releases could be larger than presently predicted. Research is in progress to develop the database and models needed to make more accurate predictions and to determine what steps, if any, should be taken to mitigate the effects of gas generation. Consequences of gas generation have not been explicitly addressed in the calculations thus far.

If future simulations of performance following intrusion continue to show a possibility of releases exceeding potential regulatory limits, design modifications may be necessary to reduce the potential for radionuclide transport up a borehole. This report presents analyses to show that significant reductions in the porosity and permeability of the waste or in radionuclide solubility through engineered modifications could assure compliance with Subpart B of the vacated Standard even without effective borehole plugs.

Engineered modifications being researched could reduce waste permeability and radionuclide solubility and alleviate potential problems of gas generation. These modifications would be designed to reduce the removal of radionuclides during and after an intrusion. Alternatives that are feasible with present technology are available and could assure acceptable performance. Experimental data and interpretations made during testing could indicate, however, that extensive engineering modifications are not required; furthermore, health and safety risks from waste treatment could be unacceptably high relative to benefits for long-term isolation. It would be inappropriate to recommend specific engineered modifications at this time.

SNL believes the WIPP Project can achieve compliance with Subpart B of the 1985 Standard. The Project is pursuing concurrent and parallel paths to assure compliance. Following the original path, SNL will continue to acquire the database and develop the models needed for adequately predicting repository performance as currently designed because this design is considered adequate. Research will evaluate methods to mitigate gas effects and better calculate their consequences. Because the outcome of ongoing research cannot be predicted now, however, two additional paths, implementing passive institutional controls and investigating alternative waste forms and repository designs, are being examined simultaneously to provide more confidence in compliance. Repository-design or waste-form modifications may or may not be required, but they are being evaluated and tested so that they will be available if necessary.

Scientific and engineering investigations are now directed at finding the optimal solution to the "reasonable expectation of compliance" required by the 1985 Standard.

I. INTRODUCTION

Before the Waste Isolation Pilot Plant (WIPP) may begin service as the United States' first repository for the permanent disposal of transuranic radioactive waste generated by government defense programs, the Department of Energy (DOE) must establish compliance with applicable environmental and safety regulations. This report addresses one major regulation, the United States Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (40 CFR Part 191; U.S. EPA, 1985), hereafter referred to as the Standard. Consideration is limited to Subpart B of the Standard, the Environmental Standards for Disposal. The report does not address other regulations such as those implementing the Resource Conservation and Recovery Act of 1976 (RCRA). Concerns about other regulatory and safety issues are important, and they will be addressed in other documents.

PURPOSE

The purpose of this report is to assure that compliance with disposal standards is achievable for the WIPP. In part, the report was prepared because review and oversight groups have recommended that the status of knowledge about potential performance of the repository be assessed before waste-emplacement for testing begins. Much information summarized here is published elsewhere in greater detail (Lappin et al., 1989; Marietta et al., 1989; Bertram-Howery et al., 1989; Recharad et al., 1990; Butcher, 1990; Guzowski, 1990a; U.S. DOE 1990a,b,c).

Sandia National Laboratories (SNL), Scientific Advisor for the WIPP Project and the organization responsible for scientific investigations and assessments of repository performance, is confident the WIPP Project ultimately will comply with EPA's standards when they are repromulgated. Performance of the repository as presently designed is believed to be acceptable, but in the event that ongoing research should indicate otherwise, effective and feasible options for improving performance are being investigated (U.S. DOE, 1990c). Selected alternatives will be tested during the WIPP Test Phase (U.S. DOE, 1990b) and will be available for implementation if research indicates they are appropriate and necessary.

The currently available data do not support definitive assessments of compliance, and it would be inappropriate for the DOE to base a repository decision on the incomplete evidence now available. The present modeling system is adequate for analyses to guide further research, but additional data

acquisition and modeling refinements are necessary to increase confidence in the measure of performance before determining what, if any, improvements in repository performance will be required to achieve compliance. Regulatory compliance cannot be formally determined at this time, but because effective options for improving performance will be available if needed, future achievability of compliance with the requirements of the 1985 Standard is not in doubt. The major question remaining is not whether the WIPP can comply with the Standard, but rather how it should comply.

40 CFR PART 191, SUBPART B

The Standard was remanded to the EPA by the United States Court of Appeals for the First Circuit in July 1987. Although Subpart B was entirely vacated by the Court and could be substantially revised, the DOE, in keeping with the 1987 amendment to the agreement between the DOE and the State of New Mexico (U.S. DOE and State of New Mexico, 1981), is evaluating compliance with the Standard as first promulgated. The DOE is making available to the EPA knowledge gained during research for the WIPP Project to help insure a workable and realistic Standard. Without some assurance that the Standard can be implemented, the feasibility of geologic disposal cannot be demonstrated. As stated in the preamble published in the Federal Register with the Standard, it is EPA's intent that compliance "should not significantly increase the cost or difficulty of carrying out the national program for disposing of the wastes..." (U.S. EPA 1985, p. 38067, column 3). This goal would be in question if extensive modifications are required to assure compliance of the WIPP.

For the purposes of this report, the relevant portions of Subpart B as first promulgated are the Containment Requirements (§ 191.13), the Assurance Requirements (§ 191.14), and the Individual Protection Requirements (§ 191.15). The Containment Requirements, discussed further in Chapter II, set limits on the probability (likelihood) that cumulative radionuclide releases during the 10,000 years following decommissioning will exceed limits calculated as specified. These limits are expressed in probabilistic rather than absolute terms, and assessments of repository performance must take into account "all significant processes and events that may affect the disposal system" (§ 191.13[a]). The approach presented here, therefore, cannot be compared with that recently reported in the WIPP *Final Supplement Environmental Impact Statement* (FSEIS) and supporting documents, in which analyses of performance were not required to be probabilistic, and which considered only expected and degraded conditions (Lappin et al., 1989; U.S. DOE, 1990a). Although the Containment Requirements do not limit radiation doses to humans, the FSEIS assessments included dose calculations as an additional measure of repository safety and concluded that even under worst circumstances considered, doses to

the general public would be minimal and below or near currently recommended guidelines (Lappin et al., 1989; U.S. DOE, 1990a).

Because future events can not be predicted absolutely, the Containment Requirements state that compliance will be judged on the basis of a "reasonable expectation" of acceptable performance. Although the Standard does not define "reasonable expectation," it does indicate that compliance assessments should include both quantitative numerical simulations of disposal-system performance and qualitative expert judgment. As discussed in Chapter IV, experts will evaluate unknowns such as future human actions, for which data are unobtainable. Expert judgment will also define the term, "reasonable expectation," to guide probabilistic predictions of the WIPP's performance. Chapter II discusses the process for quantitatively predicting long-term performance with probabilistic numerical simulations.

The Assurance Requirements (§ 191.14) outline steps the DOE must take to provide additional assurance of regulatory compliance following the decommissioning of the repository. Requirements addressed here are maintaining institutional control as long as possible, designating the disposal site with permanent markers, and using both natural and engineered barriers to isolate the waste.

The Individual Protection Requirements (§ 191.15) limit annual radiation doses resulting from undisturbed performance of the repository over a 1,000-year period. These requirements also stipulate that compliance will be based on a "reasonable expectation" of acceptable performance. Compliance must be demonstrated separately for § 191.13 and § 191.15.

The Ground Water Protection Requirements of the vacated Standard (§ 191.16) regulate releases only for sites containing aquifers that "are supplying drinking water for thousands of persons as of the date [the site was selected, and] ... are irreplaceable in that no reasonable alternative source of drinking water is available to that population" (§ 191.12[o]). Because such a "special source of ground water" (§ 191.16[a]) does not exist at the WIPP, the 1985 Ground Water Protection Requirements are not relevant. All ground water in the immediate vicinity of the repository is highly saline. This saline ground water includes pressurized brines in the Castile Formation that underlies the repository, interstitial brine in the Salado Formation hosting the repository, and locally significant volumes of brine in the overlying Culebra Dolomite Member of the Rustler Formation.

These requirements may change when the Standard is reissued, although the Court did not specifically object to the Containment Requirements or the Assurance Requirements. The Court found that the EPA had not fully reconciled the Individual Protection Requirements of the Standard with Part C of the Safe

Drinking Water Act. The Court also found that the EPA had not adequately explained the basis for the 1,000-year criterion in the Individual Protection Requirements and that, furthermore, the Ground Water Protection Requirements had been promulgated without proper notice. Compliance plans for the WIPP will be revised if necessary in response to any changes that may result from the Court's decision (Bertram-Howery et al., 1989).

The DOE will determine compliance for the WIPP on the basis of SNL's planned 1994 document, *Comparison with 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant* (hereafter referred to as the *Comparison*). That report will describe the compliance-evaluation process and compare the WIPP's performance with the requirements of Subpart B. A planning draft (Bertram-Howery et al., 1989) has been published to afford review and oversight groups an opportunity to assist in establishing the format and scope of the *Comparison*. Review groups within the DOE include the performance-assessment team at SNL, the WIPP Management and Operating Contractor, the WIPP Project Office, the Albuquerque Operations Office, and Headquarters. Current oversight groups include the DOE Blue Ribbon Panel, the Advisory Committee on Nuclear Facility Safety (ACNFS), the Defense Nuclear Facility Safety Board, the WIPP Panel of the National Research Council's Board on Radioactive Waste Management, the New Mexico Environmental Evaluation Group (EEG), the New Mexico Environmental Improvement Division, and, informally, the EPA. The review and publication cycle for the final *Comparison* report is scheduled for 1994. Preliminary performance assessments will be reported annually in preliminary versions of the *Comparison* report beginning in 1990.

PERFORMANCE ASSESSMENT

The Standard defines performance assessment as the process for demonstrating compliance with the Containment Requirements defined in Subpart B.

"Performance assessment" means an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable. (§191.12[q])

Three parallel developmental stages are fundamental to the performance-assessment methodology for the WIPP: identifying those future events that may have a significant effect on repository performance; acquiring a database and developing numerical models capable of simulating repository performance; and

developing a procedure to assess compliance with the regulatory requirements (Bertram-Howery et al., 1989; Marietta et al., 1989).

The first stage is nearly complete. Early efforts to describe possible future events relied on "event trees," in which events or processes that could affect repository performance initiated a branching "tree" of consequences (e.g., Bingham and Barr, 1979). Possible responses of the repository were included as branches, and branch points were selected according to the variability in the parameters that controlled the responses. This system proved to be impractical, identifying an unwieldy number of "scenarios" that were neither comprehensive nor mutually exclusive, and incompatible with probabilistic analyses of parameter variability. The methodology now relies on "logic diagrams," with branch points controlled only by external events (Guzowski, 1990a); and parameter variability is incorporated directly into the database. This permits a comprehensive and fully probabilistic analysis of the disposal system using a set of scenarios defined to include all realistic future processes and events potentially affecting repository performance. The preliminary set of scenarios in current use has been narrowed to an undisturbed "base case" and 15 variations (Guzowski, 1990a). The base case (undisturbed scenario) incorporates all naturally occurring events and process including phenomena such as long-term climatic change. The 15 variations describe the consequences of human activities in the region, specifically exploration for natural resources. These scenarios may be modified and others may be added as needed. Probabilities for the scenarios will be determined by expert judgment as discussed in Chapter IV.

More work remains to be done on the second stage. The database, although extensive (e.g., Lappin, 1988; Tyler et al., 1988) and largely adequate, lacks data on some important phenomena such as gas-generation rates and potentials, radionuclide chemistry, seal efficacy, and the responses of waste-disposal rooms and surrounding portions of the Salado Formation to elevated gas pressures within the repository. Many completed computational models are being verified and, when possible, validated. Other models are still being developed. For example, scientists and engineers at SNL are striving to produce a model or models that can adequately simulate all disposal-room processes, including possible gas generation and the repository's response to any subsequent rise in pressure. Research is in progress on these topics (e.g., Bertram-Howery and Hunter, 1989; U.S. DOE, 1990b).

A significant advance in the capability to simulate repository performance has been the development of CAMCON, the Compliance Assessment Methodology CONTroller (Rechard et al., 1989). In the past, the lack of a computerized system that could link and control the individual computational models describing the various subsystems of the disposal system posed a serious problem. Without such a tool, the multiple simulations of the entire system essential for

probabilistic analyses were impractical. Analyzing the sensitivity of repository performance to variations in key parameters was also difficult. CAMCON has made it feasible to conduct repeated simulations of overall repository performance.

The third stage, developing a procedure for assessing compliance, is complete. *Performance Assessment Methodology Demonstration* (Marietta et al., 1989) documents the WIPP Project's techniques for quantitatively comparing predicted performance with the limits set by the Containment Requirements and Individual Protection Requirements. Containment results will be presented as the probability of 10,000-year cumulative radionuclide releases to the accessible environment, defined by the Standard to mean the atmosphere, surface waters and oceans, the ground surface above the repository, and the subsurface beginning at a horizontal distance no greater than 5 km from the waste panels (§191.12[g,k]). As required by the Standard, these results will incorporate the probability of occurrence for each scenario analyzed. For the Individual Protection Requirements, projections of the 1,000-year undisturbed performance of the repository will be presented as annual doses to individuals within the accessible environment. Both projections will incorporate parameter uncertainty and reflect all appropriate conceptual models of the disposal system.

RECOMMENDATIONS OF OVERSIGHT GROUPS

Oversight groups agree that available evidence indicates the WIPP will comply with Subpart A of the Standard, which regulates repository performance during the test and operational phases. Because complications are introduced by considering inadvertent human intrusion into the repository after it is decommissioned, compliance with the Containment Requirements of Subpart B remains uncertain. The ACNFS suggests, however, that current human-intrusion scenarios may be unrealistic, and their simulation may therefore unnecessarily overestimate releases. Specifically, conservative assumptions about the probability of intrusion, the permeability of future borehole plugs, and the effectiveness of markers and records in protecting the repository from intrusion have been questioned. Some reviewers have suggested that the DOE develop an intrusion scenario allowing for the possibility intruders will seal the intruding borehole as carefully and effectively as they can, reflecting the belief that future human behavior will include reasonable measures to protect society and the environment.

The EEG recommends that preliminary performance calculations should include the possible effects of gas generated as waste and containers decompose. Research has been initiated to investigate consequences of gas generation and repository pressurization in both the undisturbed state and in the event of an intrusion (Rechard et al., 1990). Quantitative modeling of gas generation,

repository pressurization, and gas flow are in preliminary stages and are not yet adequate for performance calculations.

Several oversight groups suggest the DOE should examine the possibility that modifying the repository or the waste form could assure compliance with the vacated Subpart B, even using EPA's pessimistic guidance about human intrusion. Research on limiting radionuclide release after an intrusion is in progress. Research on eliminating undesirable effects of overpressurization resulting from gas generation within the repository is also in progress.

The EEG has inquired about the status of the DOE plan to comply with the Assurance Requirements. Two of these requirements are closely related to human intrusion. One requires that the "disposal site shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location" (§ 191.14[c]). Another indicates that "both engineered and natural barriers shall be included" in the disposal system isolating the waste (§ 191.14[d]). This report concentrates on passive institutional controls and engineered barriers for preventing excessive radionuclide releases resulting from inadvertent human intrusion.

THE WIPP TEST PHASE

Congress created the WIPP in 1979 (Public Law 96-164) to provide "a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission." The fundamental mission, demonstrating safe disposal of transuranic wastes, is being fulfilled in a phased approach, leading to the decision whether the WIPP can be designated a repository. The WIPP Project is completing preparations to initiate the next major developmental stage: the Test Phase. Designed to collect additional technical data to improve confidence in predicting the long-term performance of the repository, the Test Phase will include the first receipt of waste (for gas-generation tests) and will continue for about five years (U.S. DOE, 1990b).

Accurately simulating behavior of the disposal system requires data derived from experiments conducted in the laboratory as well as in the WIPP underground. Scientific investigations have been conducted since 1975. These studies resolved many technical issues and focused attention on aspects still requiring investigation. Performance assessment and disposal system characterization studies will continue during the Test Phase. These studies are guided by iterative sensitivity analyses and disposal-system-performance

calculations. Bertram-Howery and Hunter (1989) mapped the contribution of all activities in the scientific program to the performance assessment.

The scheduled late-1994 publication of the *Comparison* is predicated on obtaining required data from the experimental program such that parameter and system uncertainties are sufficiently reduced and the DOE has reasonable expectations that the WIPP complies with the Standard. Until issuance of the *Comparison*, the WIPP Project will perform a preliminary performance assessment every six months, using the most recent models and data sets available from the experimental activities. The results of these interim analyses will be provided in briefings to the oversight groups every six months, and documented in the preliminary *Comparison* to be published annually.

Four major areas of scientific investigation integral to the assessment of disposal-system performance require both laboratory and large-scale underground tests. These investigations examine the behavior of the disposal-room and drift system, behavior of the sealing system, structural deformation and fluid flow in the Salado Formation, and non-Salado hydrology and radionuclide migration.

Two activities of special interest to performance-assessment analyses are the gas-generation tests and the engineered alternatives study. Gas-generation tests assume an incremental scaled approach to testing, from laboratory experiments to underground bin tests of waste/backfill combinations to underground emplacement of more representative experiments in specially excavated test rooms that will each contain about 1000 drums of waste. Potential engineered alternatives, including six modifications to the waste form and three backfill alternatives, will be incorporated into the laboratory and underground tests. The DOE recognizes that experimental data and interpretations made during the Test Phase could indicate that extensive engineering modifications are not required; moreover, health and safety risks from waste treatment could be unacceptably high relative to benefits for long-term isolation. In 1994, following evaluation and testing, the Project will recommend specific engineered modifications, if any are required.

UNDISTURBED PERFORMANCE OF THE REPOSITORY

Calculations to date indicate excellent undisturbed performance. No radionuclides whatsoever are predicted to reach the accessible environment within the 1,000-year period specified by the Individual Protection Requirements--nor even during the 10,000-year period specified for evaluations of disturbed performance (Lappin et al, 1989; Marietta et al., 1989; U.S. DOE, 1990a). SNL has high confidence in undisturbed performance, provided there are no unexpected consequences of gas generation within the waste-disposal rooms.

Undisturbed performance of the repository as currently designed is predicted to satisfy EPA requirements by orders of magnitude (Marietta et al., 1989). Activities planned for the Test Phase, such as large-scale seal tests and laboratory experiments on gas getters in backfill, are designed to evaluate expected seal and backfill performance (U.S. DOE, 1990b).

Predictions of excellent undisturbed performance are not unexpected. The location was selected because of exceptional geologic and hydrologic barriers to radionuclide migration (Powers et al., 1978). Significant radionuclide transport occurs only in a liquid medium, and salt, the primary component of the Salado Formation that contains the repository, even given the recent debate about brine seepage, is among the driest and least-permeable rock types known. The approximately 600 m of layered salt in the Salado Formation have remained undisturbed since they were deposited during the Late Permian Period, 255 million years ago. This period of geologic stability is roughly twice the time required to create the South Atlantic Ocean through seafloor spreading (Larson and Ladd, 1973), six times the time required to create the Himalaya Mountains (Searle et al., 1987), and 25,500 times greater than the 10,000-year period of regulatory concern. No geologic processes are likely to disturb the repository for many millions of years (Powers et al., 1978). The region is not subject to active faulting and earthquakes, and igneous activity has not occurred in the vicinity of the repository since mid-Tertiary time, 35 million years ago. Major volcanic activity last occurred over 1 billion years ago, during Precambrian time. The repository is sufficiently deep (approximately 650 m below the ground surface and 350 m below the top of the Salado Formation) that natural erosion processes are extremely unlikely to expose it within millions of years. Dissolution of salt in the subsurface has occurred elsewhere in the region (Bachman, 1987), but in the immediate vicinity of the repository the Salado Formation has remained intact since its deposition.

Salt is ideal for waste disposal because it deforms by gradual creep processes under lithostatic pressure. Fractures in salt heal over time, and broken or crushed salt will eventually reconsolidate under pressure to its original form. Excavated disposal rooms will creep closed around the waste, encasing it in salt ultimately as impermeable as the undisturbed Salado Formation. Repository seals are designed to take advantage of salt creep. Concrete and bentonite plugs in the shafts and between the panels will provide effective barriers to fluid flow and radionuclide migration during the first centuries after decommissioning, while salt backfill between the plugs consolidates to seal the repository permanently (Tyler et al., 1988).

Preliminary calculations of undisturbed repository performance have not explicitly included possible effects of gas on the repository. Available models are not sophisticated enough to simulate all aspects of gas generation, and data on gas volumes and rates at which gas forms and subsequently disperses

from the repository are inadequate to quantify responses to possible rises in pressure. Calculations for the FSEIS assumed, however, that sufficient gas will be generated to bring fluid pressure in the repository up to lithostatic pressure more rapidly than without gas generation, slowing creep closure and preventing fractures from healing for 2,000 years (U.S. DOE, 1990a). The logic behind presently estimated gas-generation rates and total gas-generation potentials is documented in Lappin et. al (1989). Future simulations of undisturbed performance will employ quantitative models of gas generation and repository response, but such simulations are expected to predict no significant radionuclide release. As discussed in Chapter VI, a primary effect of elevated gas pressures within the repository will be to slow or halt the gradual seepage of brine into the waste-disposal area, and as long as the repository remains dry, radionuclide transport cannot occur. Gas generation therefore has the potential to enhance undisturbed performance.

HUMAN INTRUSION

Because acceptable undisturbed repository performance is anticipated, performance-assessment work is concentrating on the consequences of inadvertent breaching of the repository by an exploratory borehole. The guidance for the Containment Requirements suggests inadvertent intrusion by exploratory drilling for resources may be the most severe human-intrusion scenario. Because natural disturbance is unlikely, human intrusion is the most severe disturbance considered for the WIPP performance assessment.

The WIPP is located in a sedimentary basin already extensively explored for hydrocarbons and other minerals (such as potash), thus performance assessments should consider the possibility that a future exploratory borehole could intersect a waste-disposal area. The probability that such an intrusion will occur is discussed further in Chapter IV. Preliminary simulations of human-intrusion scenarios suggest that, assuming expected favorable conditions, the disposal system will comply with the Containment Requirements. Preliminary calculations, however, indicate radionuclide releases to the accessible environment could exceed allowable limits if several unfavorable conditions coincide (Lappin et al., 1989; Marietta et al., 1989; U.S. DOE, 1990a). Calculations to date either assume intrusion would occur or assume some probability of occurrence. As a result, the human-intrusion scenario dominates performance assessments, overshadowing the sound geologic reasons for selecting the location. This emphasis may not be necessary: the probability that the assumed conditions and circumstances will occur remains to be formally estimated (see Chapter IV).

Discussions of scenarios considered in the performance assessment and the logic for ordering them can be found in Marietta et al. (1989), Bertram-Howery et al. (1989), and Guzowski (1990a).

THE E1 SCENARIO

A single scenario is used in this report to illustrate how the options considered can affect predictions of repository performance following human intrusion. One scenario is simulated for sensitivity analyses to simplify computations and insure commensurable results. SNL selected the E1 (event one) scenario (Marietta et al., 1989) because it incorporates aspects of all presently recognized modeling problems associated with simulating intrusion. The analysis presented here is not a performance assessment because formally evaluating compliance requires considering all significant scenarios, including significant combinations of events resulting in intrusion by more than one borehole.

The E1 scenario comprises a hypothetical exploratory borehole drilled through a waste-filled room or drift in the repository and into a pressurized-brine reservoir in the underlying Castile Formation (Figure 1-1). As in any drilling scenario, some waste is incorporated in the circulating drilling fluid and is released at the surface during drilling. Radionuclides could also reach the accessible environment, albeit much more gradually, after the drillers plug and abandon the hole. Pressure gradients could drive brine through the waste and up the hole, through the plugs, and into the Culebra Dolomite Member of the Rustler Formation above the repository. Long-term release occurs in the subsurface when radionuclides transported laterally by ground water in the Culebra Dolomite Member reach the accessible environment. Radionuclide transport is considered only for the Culebra Dolomite Member because it has been identified as the most likely pathway for transport to the accessible environment. Transport in other units will be considered in future work, if warranted by new data.

Scenario E1 incorporates the worst events that must be hypothesized to affect repository performance, according to the guidance provided by the 1985 Standard. As discussed further in Chapter II, the Standard does not require that worst-case calculations be used to evaluate compliance, but they can be used to bound long-term repository performance. The scenario is also useful for performance-assessment work because it incorporates all events significantly complicating compliance; thus, it is valuable for showing how sensitive predictions are to changes in any single controlling parameter. Chapters III and V discuss sensitivity analyses that examine the ways specific parameters affect predictions of performance for this scenario. For example, potential benefits of engineered modifications that could reduce brine flow through the

R_c = Release of Cuttings and Eroded Material

R_{acc} = Release at the Subsurface Boundary of the Accessible Environment

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Figure 1-1. Conceptual model for Scenario E1. Arrows indicate assumed direction and relative magnitude of flow (Marietta et al., 1989).

waste are evaluated by varying values for porosity and hydraulic conductivity within the repository.

Choosing scenario E1 for preliminary performance assessments does not imply that intrusion is inevitable, nor that compliance should be based on calculations that assume its occurrence. The EPA's intent in the regulation is to judge the performance of the repository on the probable circumstances of the next 10,000 years, rather than on the worst conceivable circumstances. As discussed in Chapter IV, the probability that intrusion will occur is still undetermined.

PROGRAMMATIC APPROACH

The WIPP Project is concurrently pursuing three paths to assure compliance with the Standard. The first path continues researching and evaluating the performance of the disposal systems as designed to improve the ability to predict performance. The second path examines current assumptions about the consequences of human intrusion and evaluates ways to reduce the probability and delay onset of intrusion through the use of passive markers above the repository. The third path investigates alternatives to the current design that could improve performance if necessary and thereby assure compliance. Because changes in the current design could have adverse consequences unrelated to WIPP performance, including increased safety risks and regulatory complications, modifications will not be implemented unless performance assessments indicate the need.

Work on the first path will increase confidence in predictions of performance. Uncertainties will be reduced as models improve and the database expands. Possible effects of gas generation will be evaluated. Wherever possible, assumptions and approximations will be replaced by numerical models and probabilistic distribution functions for parameter values. Future performance assessments will therefore provide sounder predictions of repository performance. Because preliminary assessments show compliance to be probable in all but the most unfavorable circumstances, SNL believes improved predictions are likely to indicate that, as currently designed, the WIPP will comply with Subpart B.

Work on the second path will provide answers for questions about the likelihood of inadvertent human intrusion and its consequences. Research will determine reasonable values for the properties of borehole plugs. Expert panels will develop criteria for passive markers to reduce the probability of intrusion, and delay as far into the next 10,000 years as possible the time when intrusion could occur. Including either a reduced probability of intrusion or

a delayed time of intrusion should increase confidence in complying with the Standard.

Compliance of the WIPP as currently designed, however, is not a certainty. Improved predictions could indicate a potential for unacceptable performance or the need to mitigate the consequences of gas generation. Uncertainties in predictions could remain too great for confident performance assessments. In either case, work on the third path, waste-form and repository-design alternatives, will provide options that can assure acceptable performance and regulatory compliance.

II. QUANTITATIVE METHOD USED TO EVALUATE PERFORMANCE

Projecting future performance of a geologic repository is made difficult by the complexity of natural systems involved, variability of parameters controlling those systems, and necessity of accounting for future human actions. The Standard recognizes this problem.

Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of what is before the presenting agency, that compliance with 191.13(a) will be achieved. (§ 191.13[b])

The Standard does not specify the evidence needed to generate this "reasonable expectation." Appendix B of the Standard does suggest in nonbinding terms, however, that the approach to establishing compliance should be two-fold.

The [EPA] believes that the [DOE] must determine compliance with §§ 191.13, 191.15, and 191.16 of Subpart B by evaluating long-term predictions of disposal system performance. Determining compliance with § 191.13 will also involve predicting the likelihood of events and processes that may disturb the disposal system. In making these various predictions, it will be appropriate for the [DOE] to make use of rather complex computational models, analytical theories, and prevalent expert judgment relevant to the numerical predictions. Substantial uncertainties are likely to be encountered in making these predictions. In fact, sole reliance on these numerical predictions to determine compliance may not be appropriate; the [DOE] may choose to supplement such predictions with qualitative judgments as well.

EPA suggests the final measure of compliance should include qualitative judgments about the reasonableness of the numerical simulations quantitatively predicting repository performance.

Following this guidance, efforts to evaluate regulatory compliance have concentrated to date on developing a comprehensive computational system capable of predicting overall repository behavior. Detailed numerical models for most components of the repository (e.g., salt creep and room closure, fluid flow through seals, and ground-water flow in the overlying units) were developed during site characterization and repository design (Lappin, 1988; Tyler et

al., 1988). Some data and models are being updated, and other models are still under development. Appropriately linking and streamlining these models and analyzing the results could, in theory, provide a quantitative test of compliance.

DETERMINISTIC ANALYSES (HISTORICAL APPROACH)

Analyses of repository performance prior to EPA's promulgation of the Standard were deterministic: they assumed fixed values for model parameters. An example is the *Final Environmental Impact Statement* (FEIS) for the WIPP (U.S. DOE, 1980). The *FSEIS* continued the deterministic approach, incorporating parameter variability by comparing deterministic cases (Lappin et al., 1989; U.S. DOE 1990a). Performance was calculated assuming the simultaneous occurrence for most parameters of expected values and compared to predictions assuming values that greatly increase radionuclide release to the accessible environment. Such analyses tend to be conservative because they can predict releases greater than expected for normal repository performance. The probability that extreme values will coincide is not incorporated in the performance measure.

These analyses help guide research. For example, conservative, deterministic calculations indicate that radionuclide releases to the accessible environment from an undisturbed repository will not occur. If several conservatively selected parameter values coincide, predicted releases to the accessible environment following human intrusion could exceed allowable limits by less than an order of magnitude, while if expected parameter values occur, releases are within allowable limits (Lappin et al., 1989). Further research is therefore directed toward quantifying and controlling releases resulting from intrusion. Deterministic calculations are not, however, applicable to evaluating compliance of the repository with Subpart B.

PROBABILISTIC ANALYSES (40 CFR 191 APPROACH)

Variability inherent in natural properties controlling repository performance precludes assigning absolute and constant values to model parameters. Values for each parameter must be reported as a range. For any particular parameter, the distribution of values within the range may be known, and it may be possible to determine an "average" or "expected" value, but it is seldom possible to eliminate extreme values. The probability of the extreme value occurring can be estimated, and should be low.

The Containment Requirements state that performance must be measured in probabilistic terms. The allowable radionuclide release is not a single, fixed

quantity, but rather is a function of the probability that the events and parameter values that contribute to the release will occur. Specifically,

cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

- (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated [as specified]...and;
- (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the [above] quantities.... (§ 191.13[a])

In other words, the more restrictive limits apply to those releases with a probability greater than 1 chance in 10 (>0.1) of occurring during the next 10,000 years. For releases with a probability between 1 in 10 and 1 in 1,000, limits are increased ten-fold. Releases with probabilities less than 1 in 1,000 (<0.001) are not limited. Numerical limits have been placed not on predicted cumulative radionuclide releases, but rather on the probability that cumulative releases will exceed quantities calculated as prescribed (Figure 2-1).

Compliance with the Containment Requirements, therefore, can be evaluated quantitatively only through probabilistic analyses. Available models for repository performance are all deterministic, however, and simulations must be performed using specified values for input parameters. Probabilistic analyses can be performed with deterministic models, but they require multiple simulations using input data probabilistically selected by sampling over the full range for each parameter.

Probabilistic performance analyses can be understood conceptually through the following "thought experiment" (Tierney, 1990). Consider many replicas of the repository and its geologic environment, each constructed to identical design specifications and each filled with the same volume of waste drawn from the same sources. These hypothetical repositories are not identical, but they are as close to identical as is possible within the unavoidable variability inherent in design, construction, and environmental parameters. Because of this variability, each replica will perform differently over the next 10,000 years, and cumulative radionuclide releases from each will be different. If human intrusion is excluded from the experiment, a histogram showing these cumulative releases would be suitable to measure probabilistic repository performance in the undisturbed state. If human intrusion is allowed and if the number of replicas is sufficiently large to include low-probability events, the distribution of cumulative releases could, in theory, be used to predict regulatory compliance for any one replica.

<u>Region</u>	<u>Likelihood</u>	<u>Allowable Release</u>
Ia	1 in 10 or More	Less Than Limit
Ib	1 in 10 or More	None
Ila	1 in 1000 to 1 in 10	Less Than 10 Times Limit
I Ib	1 in 1000 to 1 in 10	None
III	0 to 1 in 1000	Total Inventory

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Figure 2-1. Containment Requirements. Each region represents a range of probabilities for a range of releases. In probability Region Ia, the release is less than the limit. In probability Region Ila, the release is less than ten times the limit. In probability Region III, the release is not limited. In probability Regions Ib and I Ib, releases exceed the limit.

Given a mathematical model describing repository performance and probabilistic data about the variability of each significant parameter, numerical simulations can mimic the hypothetical experiment. Multiple simulations can be performed incorporating both initial variability and the probabilities of different future events, such as human intrusion, that could affect performance. These simulations produce the quantitative performance assessment required by the Standard.

THE COMPLEMENTARY CUMULATIVE DISTRIBUTION FUNCTION

If repository performance is repeatedly simulated, results can be plotted as a complementary cumulative distribution function (CCDF). CCDF plots are discussed here qualitatively. More detail on constructing and interpreting CCDFs for the WIPP performance assessment can be found in Marietta et al. (1989), Rechard (1989), and Bertram-Howery et al. (1989) (also see Cranwell et al., 1982; Pepping et al., 1983; Hunter et al., 1986; Campbell and Cranwell, 1988; Tierney, 1990).

Ultimately, CCDF plots showing the probabilistic, cumulative, radionuclide release to the accessible environment will be used to evaluate regulatory compliance quantitatively. Appendix B of the Standard indicates that "the [EPA] assumes that a disposal system can be considered to be in compliance with § 191.13 if this single distribution function meets the requirements of § 191.13(a)." A numerical CCDF plot may therefore be sufficient to establish compliance. The Standard implies that the disposal system is not necessarily in noncompliance if a CCDF curve exceeds the specified limits. The Containment Requirements state that, based upon performance assessments, releases shall have probabilities not exceeding specified limits. This would mean noncompliance if the CCDF exceeded the limits; however, § 191.13 also states that performance assessments need not provide complete assurance that the requirement will be met and that the determination should be "on the basis of the record before the [DOE]." Given the discussions on use of qualitative judgment in Appendix B, this means the entire record, including qualitative judgments. As discussed below, the likelihood that excess releases will occur must be considered before a qualitative decision can be made about a "reasonable expectation" of compliance.

Conceptually, the CCDF graphs probability versus cumulative radionuclide release for all significant scenarios (Figure 2-2). The curve is plotted as a step function, with each step reflecting how parameter variability affects one simulation of disposal system performance under a single scenario. Compliance

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Figure 2-2. Hypothetical CCDF illustrating compliance with the Containment Requirements (modified from Rechar, 1989). The shaded region exceeds the limits set by the Containment Requirements.

can be evaluated quantitatively by comparing a correctly constructed CCDF curve to the limits prescribed by the Standard (see Figure 2-1).

CCDF plots are constructed as follows. Probabilistic distribution functions are assigned to all parameters, and those distributions are statistically sampled to insure that all possible values, including extreme outliers, are properly represented. Performance is simulated using the selected parameter values, and for evaluating compliance, each resulting set of release values is weighted by the probability that the scenario simulated by that set will occur. All significant scenarios are simulated repeatedly, and the final composite plot reflects the probabilistically predicted overall repository performance. Multiple plots can result from multiple conceptual models.

Because each simulation samples different parameter values, no two simulations will be identical. As in the thought experiment described above, each simulation will reflect a different (and deterministic) history for the repository, and predicted releases will vary according to the variability inherent in the entire system. Therefore, no single simulation can be definitive. Separate simulations performed using the same distribution functions for all parameters may result in significantly different cumulative releases. If the random number initializing the sampling is changed for each set of simulations, a set of possible CCDF curves is generated with a distribution for which a statistical mean and confidence level can be determined.

The regulatory significance of CCDF plots is complicated by the variability inherent in the function and the Standard's requirement that compliance be based on a "reasonable expectation" of acceptable performance. For example, coincidences of extreme parameter values have nonzero probabilities of occurrence, and represent extreme "outliers" that must be considered. There may not be, however, a "reasonable expectation" that the extreme circumstances simulated will occur. Probabilistic outliers are no more appropriate for predicting long-term performance under the Standard than deterministic analyses.

At present, single-scenario CCDF plots are used extensively in performance-assessment work for comparing various intermediate results in the modeling process. Chapters III and V present such CCDF plots; they do not establish compliance or noncompliance, but they convey vital information about how changes in selected model parameters may influence performance and compliance. Because probabilities for specific scenarios and many parameter-value distribution functions are still undetermined (see Chapter IV), all CCDF plots presented in Chapters III and V are preliminary and assume only the E1 scenario (see Figure 1-1) occurs.

No "final" CCDF plots yet exist. Although the compliance limits are routinely included on all plots as reference points, the currently available plots cannot be used to judge compliance with the Containment Requirements because the plots reflect an incomplete modeling system and incomplete data and because the Standard has not been reissued following remand. It will not be possible to determine compliance until the final regulatory limits are available and until improvements in the modeling system and the database fully support predicting repository performance.

ASPECTS OF PERFORMANCE MODELING

Fully simulating repository performance will require a complex system of linked models and an enormous database. All simulations to date, including both deterministic (Lappin et al., 1989; U.S. DOE, 1990a) and probabilistic (Marietta et al., 1989) calculations have been based on numerous simplifying but generally conservative assumptions. In part, this is because some model components of the system are not yet fully developed, and portions of the database are still being researched. Improved models and new data will be incorporated into the modeling system as they become available. Simplifying assumptions cannot be eliminated entirely from a mathematical modeling system because models cannot duplicate the complexity and variability of a natural system.

Simplifying assumptions also serve a pragmatic function. At present, the most complex simulations of repository performance take several hours of supercomputer time. Simplifications to streamline computational models substantially reduce that time. With the current number of parameters varied, a probabilistic analysis of a single scenario will require 35 to 50 simulations. There are currently sixteen scenarios that will require separate analyses. Increasing model complexity and expanding the database will increase both the time required for a single simulation and the total simulations necessary for evaluating compliance with the Standard. Sensitivity analyses that must be made before final simulations can be attempted will require numerous additional simulations. Today's computers will be inadequate for the task unless the modeling system is kept as simplified and streamlined as possible.

Deterministic calculations have used assumptions that permit simulations of optimistic and pessimistic bounds for repository performance following intrusion (Lappin et al., 1989; U.S. DOE, 1990a). Probabilistic calculations to date have used the same assumptions to insure consistency (Marietta et al., 1989). The choice of these assumptions has been guided by a conservative philosophy. Where parameter values are unknown or where models inadequately simulate performance, assumptions have been made that, in general, predict radionuclide releases greater than would be predicted were data or models

available. This conservative approach precludes unduly optimistic predictions of repository performance. The approach may also, however, result in unnecessarily pessimistic predictions. Performance is unlikely to be worse than presently predicted. It may be substantially better, but the magnitude of possible improvement will not be known until modeling and database development permit more complete simulations.

CONSERVATIVE ASSUMPTIONS

The implications of conservative assumptions must be understood before the preliminary predictions of repository performance can be interpreted. All simulations, from the most optimistic to the most pessimistic, have included assumptions that overestimate radionuclide releases.

Both deterministic and probabilistic calculations to date have been conditional on the occurrence of intrusion (i.e., an intrusion is assumed to occur). This assumption may be unnecessarily pessimistic because it takes no credit for the contribution of a passive marker system in reducing the likelihood of intrusion. Calculations that take into account the time and probability of intrusion should be completed in late 1990.

Predictions of releases following intrusion have assumed that flowing brine will remove radionuclides from an entire panel of seven disposal rooms. Actual flow is likely to be more restricted (Rechard et al., 1990), and the amount of radionuclides available for transport up the intruding borehole may be substantially less than in the current pessimistic predictions.

As discussed again in Chapter III, Lappin et al. (1989) and Marietta et al. (1989) have also used several assumptions about flow within the intruding borehole that tend to increase predicted radionuclide releases. Borehole plugs were considered to be no more effective than sand and rubble. Lappin et al. (1989) assumed that plugs would deteriorate completely within 150 years after emplacement. No credit was taken for the possibilities that the borehole will be plugged more effectively by the intruders or that the hole may be resealed partially or entirely by salt creep or salt deposition. In all simulations to date, the pressure gradient driving brine flow up the hole was assumed to remain constant for the entire 10,000-year period at the maximum pressure observed in Castile Formation brines near the repository. It is possible instead that initial pressure could be substantially lower and there could be a pressure drop and a consequent decrease in flow as the brine reservoir in the Castile Formation is depleted. Calculations that allow for pressure dissipation and variable initial pressure are in progress and should be completed in late 1990.

Calculations by Lappin et al. (1989) and Marietta et al. (1989) assumed that radionuclide transport within the Culebra Dolomite Member of the Rustler Formation would be by one-dimensional, single-porosity fracture flow with little radionuclide retardation. Revised deterministic calculations using a more-realistic, two-dimensional, dual-porosity model with both fracture and matrix flow show this to be a pessimistic assumption (U.S. DOE, 1990a). Radionuclide retardation within matrix porosity may further reduce releases. Preliminary probabilistic simulations using dual-porosity flow and variable matrix retardation will be completed in June 1990.

Deterministic calculations by Lappin et al. (1989; also see U.S. DOE, 1990a) included several other conservative assumptions. The most important describe decay of radionuclides during the period of regulatory control. For undisturbed performance, credit is taken only for the first 2,000 years of radioactive decay, during the time the repository is assumed to be gas filled. Transport is assumed to begin as soon as the repository is brine saturated, and further decay of radionuclides during transport is not included in calculations. For intrusion scenarios, either no credit was taken for radioactive decay prior to intrusion, or credit was taken only for decay during 100 years of active institutional control. An intrusion occurring many hundreds or thousands of years in the future, after large quantities of radionuclides had decayed, would result in substantially smaller releases than predicted by these calculations.

OTHER UNCERTAINTIES

Not all assumptions made to resolve modeling uncertainties are so clearly conservative or pessimistic. In some cases data are insufficient to determine a suitable range of parameter values, and in other cases, appropriate models are not yet available to simulate the phenomenon in question. Research is in progress to acquire data and develop models that will improve the Project's ability to predict repository performance (U.S. DOE, 1990b). If improved predictions indicate the need, modifications such as those described in Chapter VII may be used to assure acceptable performance (U.S. DOE, 1990c).

For example, current data and models do not permit quantitatively predicting gas generation and the repository's response to possible increases in pressure. As discussed in Chapter VI, present conceptual models of repository response to gas generation, particularly following human intrusion, are speculative. It is not known to what extent the conservative and pessimistic gas-free calculations bound the consequences of gas generation. Modifications could be required to mitigate the effects of gas generation.

As discussed in Chapter III, the assumption that no more than three drum-equivalents of waste will be brought directly to the ground surface during an

intrusion is believed to be conservative, but neither data nor current models permit a more accurate prediction of the release. If necessary, modifications that increase the shear strength of the waste could reduce this component of the total radionuclide release.

Other assumptions embedded in many aspects of the modeling serve as surrogates for process models or data. Radionuclides are assumed to be transported in the Culebra Dolomite Member of the Rustler Formation as solutes only, with no allowance for possible transport as colloids or particulates. Flow in the Culebra Dolomite Member is assumed to be controlled by a transmissivity field that must be approximated from available borehole data. Results to date have not included possible changes in ground-water flow due to long-term climatic changes, although such simulations are currently in progress. Modeling flow in the Culebra Dolomite Member has not allowed for the possibility that the material properties of the unit, specifically the transmissivity field, may change over time. This is believed to be an unlikely event, but simulations including such changes are planned for 1991. All assumptions, conservative and otherwise, are being tested as models and data permit.

Until the Project is satisfied that models and database are sufficient, simplifying assumptions are justified, assumptions are appropriate, and modeling uncertainties are acceptable, final determination should not be made about compliance with the vacated 1985 Standard. Until a new standard is in place, regulatory compliance legally cannot be achieved.

III. POSSIBLE CONSEQUENCES OF INADVERTENT HUMAN INTRUSION

If an exploratory borehole inadvertently intrudes into a waste-filled room or drift within the repository, radionuclides could reach the accessible environment through two pathways. One pathway is up the borehole to the surface during drilling. Cuttings, core, material eroded from the borehole walls, and brine could all contribute to this direct and immediate release. Releases could also occur along a second pathway after the hole is abandoned. As summarized in the discussion of the E1 intrusion scenario in Chapter I, fluid movement could transport radionuclides out of the repository, up the borehole, and into the Culebra Dolomite Member of the Rustler Formation or other units. Release to the accessible environment in this case would occur in the subsurface, following lateral transport in ground water.

INTERPRETATIONS OF THE REGULATORY GUIDANCE

The Standard does not contain specific information on how to evaluate the consequences of human intrusion. Appendix B of the Standard offers indirect and nonbinding guidance that is relevant but not definitive (emphasis added):

...[DOE] can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.

...Furthermore, the [EPA] assumes that the consequences of such inadvertent drilling need not be assumed to be more severe than ... [direct releases at the ground surface and the] creation of a ground water flow path with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time--not the permeability of a carefully sealed borehole. (U.S. EPA, 1985, p. 38089)

The supplementary information published with the Standard by the EPA in the Federal Register further clarifies the guidance offered in Appendix B (emphasis added):

...Appendix B to the final rule describes a set of parameters about the likelihood and consequences of inadvertent intrusion that the Agency assumed were the most pessimistic that would be reasonable in making performance assessments. The implementing agencies may adopt these assumptions or develop similar ones of their own. (U.S. EPA, 1985, p. 38077, column 1)

The EPA's implications in these paragraphs are straightforward. The drillers are likely to recognize their mistake. If they recognize the mistake and do not abandon the hole, the intrusion is no longer inadvertent, and the consequences are unregulated. The DOE's assumption that the drillers will abandon the hole is therefore conservative. In keeping with the guidance in the Standard, the DOE must consider the possibility that an abandoned hole will either remain unplugged and rubble filled or that plugs will deteriorate, becoming no more effective than rubble. The likelihood of this deterioration in salt, which was selected because of its self-healing properties, is being examined.

SHORT-TERM RELEASES AT THE GROUND SURFACE

There could be three components of the direct release of radionuclides at the ground surface during the drilling operation. Material displaced by the bit will be brought to the surface immediately, either as cuttings or as core, depending on the drilling method. The magnitude of this component will be controlled by the diameter of the borehole and the radioactivity of the waste intersected. Additional waste could be eroded from the borehole walls during subsequent, deeper drilling and carried to the surface by the circulating drilling fluid. The magnitude of this component will be controlled by the above factors and by the shear strength of the waste, which will determine the radius of erosion. Because brine present in the waste-disposal area prior to intrusion will contain dissolved radionuclides, any brine that mixes with the drilling fluid will also contribute to the total release. Preliminary calculations indicate that particulate waste from the first two components will dominate the releases at the ground surface (U.S. DOE, 1990a).

Modeling of erosion caused by circulating drilling fluid indicates that approximately three drum-equivalents of waste including cuttings or core could be brought to the surface (Lappin et al., 1989). This figure assumes a 13-1/8 inch (33.4 cm) diameter borehole and an additional 10 cm radius of erosion. The figure is believed to be conservative (Lappin et al., 1989), but more accurately simulating the radius of erosion will require data about the time-dependent shear strength of the waste. Models of borehole erosion are currently available; data for improved simulations will be available in 1991.

The amount of radionuclides in the three-drum-equivalent volume has been approximated by multiplying the average radionuclide inventory of a single drum by three (Lappin et al., 1989). This approximation simplistically assumes that drums are distributed evenly throughout the repository, and that each drum has the same radionuclide content.

Deterministic calculations of repository performance have not included radionuclide releases at the ground surface in the integrated release totals, although they have assessed the possible health risks such releases pose to the drilling crew and the general public, concluding that exposures will, at worst, be no more than roughly twice the annual dose incurred from normal background radiation (Lappin et al., 1989; U.S. DOE, 1990a). Preliminary demonstration CCDF plots presented in Marietta et al. (1989, Figure 4-17) include a deterministic estimate of direct releases from three drum-equivalents of waste that is approximately six percent of the limits specified by the Standard. Conditional CCDFs presented in this report do not include short-term releases at the ground surface, because drilling releases would be constant for the sensitivity analyses described here and would mask the sensitivity to other parameters.

LONG-TERM RELEASES IN THE SUBSURFACE

Evaluating long-term radionuclide releases following abandonment of the borehole will require data about the hydraulic properties of the hole and the material that fills it. For predictions to be probabilistic, performance assessments must establish distribution functions for these properties. In accordance with the guidance in Appendix B of the vacated Standard, one endpoint of these distribution functions could reflect conditions in a rubble-filled hole. It is the Project's responsibility to determine the endpoints and the form of the distribution functions. As is the case for all other parameters affecting repository performance, the distribution functions determined for borehole parameters should be reasonable and justifiable.

Predicting flow through a borehole will require, at a minimum, distribution functions for borehole diameters, borehole-fill porosity, and borehole-fill hydraulic conductivity. Fundamental to the discussion that follows is the assumption that future drilling technology will in some way be comparable with present technology and that future values for borehole parameters can be estimated by evaluating present parameter values. Work is in progress to develop a database on exploratory drilling, plugging, and abandonment practices in the region surrounding the WIPP.

The reasonableness of assuming comparable technology and borehole parameters can only be determined by qualitative judgments such as those described in Chapter IV. Without this assumption, however, distribution functions for borehole parameters will remain arbitrary.

A distribution function for borehole diameter can be determined from the known values for past and present boreholes. Past calculations of repository per-

formance have examined diameters from 7 to 20 inches (Lappin et al., 1989; Marietta et al., 1989; Anderson et al., 1990).

Determining distribution functions for borehole-plug and borehole-fill properties is more difficult. Appendix B of the Standard indicates that "intrusion by exploratory drilling" should be the most severe human-intrusion scenario considered. The State of New Mexico Oil Conservation Division (1989) requires plugging all abandoned boreholes, and state officials witness plugging procedures at as many sites as possible. Wildcat exploration boreholes, as opposed to production boreholes, are monitored particularly closely, and under present practices, the intruding borehole likely would be plugged at least as well as required by the regulations.

Parameter distribution functions for plugs in current use will be determined from the regional database. Assuming that regulatory requirements for plugging are met, initial flow through plugs will be negligible. Regulations in effect in the vicinity of the WIPP require a "solid cement plug through the salt section and any water-bearing horizon" (State of New Mexico Oil Conservation Division, 1988). Changes in plug properties over long periods of time pose the greatest uncertainty because plugging technology is relatively new. Calculations of repository performance to date have assumed that plugs will have deteriorated to conditions equivalent to a rubble-filled hole after 150 years (Lappin et al., 1989). This is believed to be conservative, but parameter values are difficult to quantify. Some deterioration will occur, and both the time required to reach a "final" state and the conditions at that state must be determined. Researchers are presently examining how well borehole plugs in the region have performed over the past several decades.

Nevertheless, distribution functions for borehole-fill properties used in predicting repository performance should include a wider range of values than those determined for plugs in current use. As quoted above, Appendix B of the vacated Standard provides non-mandatory guidance on one endpoint for the range. Shaft seals for the WIPP provide information about a plausible choice for the other endpoint. A suitably designed borehole plug of crushed salt and salt-compatible concrete could consolidate in response to salt creep to form an effective and permanent low-permeability barrier to fluid flow. A reasonable distribution of parameter values between these hypothetical endpoints is, as yet, undetermined.

If intruders detect the repository as suggested in the guidance to the vacated Standard, they may choose to install substantially better plugs than those required by current state regulations. Societies with the technology to drill thousands of meters exploring for natural resources will very likely also be aware of the risks inherent in breaching a radioactive waste repository. If intruders are aware of an effective plugging procedure, it is reasonable to

believe they will use it. Distribution functions for borehole parameters should include values that allow for the possibility that the intruding borehole will be plugged using the best available technology. Final distribution functions for borehole-fill parameters will therefore incorporate qualitative judgments about future human actions. Chapter IV describes the methodology for soliciting and evaluating the expert opinions needed to make these judgments.

SENSITIVITY ANALYSES OF BOREHOLE PARAMETERS

Anderson et al. (1990) examined the sensitivity of subsurface-release predictions to variations in borehole parameters by calculating a series of CCDF curves using ranges of hypothetical values for borehole diameter, borehole-fill porosity, and borehole-fill hydraulic conductivity (a measure of fluid flow dependent on permeability). These CCDF plots are not intended to convey information about overall repository performance or regulatory compliance. The calculations assume the E1 scenario occurs (are conditional on the occurrence), as described in Chapter I. Releases that may occur at the ground surface during the drilling operation have been omitted from the CCDF plots; thus, the plots show only the degree to which variations in individual parameters could influence predicted subsurface releases for a single scenario. The technique for analyzing model sensitivity to specific variations fixes a single value for each test parameter in question and varies all other parameter values probabilistically as described in Chapter II. Calculations were repeated using different fixed values of the test parameter, and comparisons of the resulting CCDF curves show the relative effect within the single scenario of varying that parameter over the specified range.

The sensitivity of the model to variations in borehole diameter was examined with a pair of simulations using fixed diameters of 7 and 20 inches. Plotted CCDF curves (Figure 3-1) are similar, and it is apparent that variation within that range will not have a major effect on subsurface releases. These results suggest that precisely quantifying a distribution function for future borehole diameters need not have a high priority. This examination of sensitivity to one parameter illustrates the value of probabilistic sensitivity analyses in guiding research.

Calculations varying borehole-fill properties show that repository performance is highly sensitive to the effectiveness of the plugs. Anderson et al. (1990) simulated performance using the "expected" and "least favorable" values selected by Marietta et al. (1989) for borehole fill. These values, 0.18 and 0.30 for porosity and 10^{-6} and 10^{-4} m/s for hydraulic conductivity, correspond roughly to the properties of silty sand and clean sand and are intended to

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Figure 3-1. Conditional CCDF curves showing sensitivity to variations in borehole diameter (D) (Anderson et al., 1990). Curves assume intrusion scenario E1 occurs. Curves were calculated using the preliminary modeling system described in Marietta et al. (1989) and cannot be used to judge compliance or noncompliance because all significant scenarios are not included, crucial models and data are missing, surface releases are omitted, and the Standard has been vacated. They simply measure modeling sensitivity to variations in the test parameter.

represent fully deteriorated plugs that are more permeable than natural materials. Calculations with the "expected" properties show little improvement over those made using the "least favorable" values (Figure 3-2).

Anderson et al. (1990) also simulated performance using the properties specified for the WIPP seals, with porosity fixed at 0.05 and hydraulic conductivity at 10^{-11} m/s. These results show very small releases compared with the Standard and plot completely off the scale to the left; the only significant release would be from materials carried to the surface during drilling, not plotted on these single-intrusion curves.

If future drillers seal an intruding borehole as carefully as the repository itself will be sealed, there will be no long-term, subsurface radionuclide releases to the accessible environment during the 10,000 years of regulatory concern (Figure 3-2). These results are not meant to imply that future drillers will install such plugs. Assuming the plugs will be better than those in common use is not unreasonable, although proving the quality of future plugs is impossible.

The point made here--and it is an extremely important point--is that improving plug parameters relative to currently assumed values will result in predictions of substantially improved repository performance. The "expected" values for deteriorated plugs and the distributions currently used for simulations could be too conservative; research is in progress to quantify realistic values. The database of drilling practices presently being developed will answer many questions. On-going investigations may shed more light on long-term material properties and degradation rates. Expert judgment may improve confidence in future drillers installing high-quality plugs.

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Figure 3-2. Conditional CCDF curves showing sensitivity to variations in borehole-plug porosity and hydraulic conductivity (Anderson et al., 1990). "Expected" and "least favorable" values for deteriorated borehole-plug porosity and hydraulic conductivity are shown. "Most favorable" values, corresponding to the properties of the repository seals, plot off-scale. Curves assume intrusion scenario E1 occurs. Curves were calculated using the preliminary modeling system described in Marietta et al. (1989) and cannot be used to judge compliance or noncompliance because all significant scenarios are not included, crucial models and data are missing, surface releases are omitted, and the Standard has been vacated. They simply measure modeling sensitivity to variations in the test parameters.

IV. PASSIVE INSTITUTIONAL CONTROL AND THE PROBABILITY OF INTRUSION

Given the approach chosen by the EPA for the disposal standards, repository performance must be predicted probabilistically to evaluate compliance. Determining the probability of intrusion poses questions that cannot be answered by numerical modeling or experimentation. Projecting future drilling activity requires knowledge about complex variables such as economic demand for natural resources, institutional control over the site, public awareness of radiation hazards, and changes in exploration technology. Extrapolating present trends 10,000 years into the future is questionable. As summarized in this chapter, all approaches to assessing drilling probability presently being considered by SNL must include expert judgment.

The Standard clearly limits future institutional control in that "performance assessments ... shall not consider any contributions from active institutional controls for more than 100 years after disposal" (191.14[a]). The Standard further requires that "disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location" (§ 191.14[c]). Analysis of the probability of human intrusion into the repository must include the effectiveness of passive institutional controls over a 9,900-year period. Such controls could substantially reduce the probability of intrusion and improve predicted repository performance.

Appendix B of the Standard contains non-binding guidance relevant to both passive institutional control and the probability of intrusion:

...The [EPA] believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). Therefore, inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed by the implementing agencies.

...The implementing agencies should consider the effects of each particular disposal system's site, design, and passive institutional controls in judging the likelihood and consequences of such inadvertent exploratory drilling. However, the [EPA] assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer per 10,000 years for geologic repositories in proximity to sedimentary rock formations... . (U.S. EPA, 1985, p. 38089)

PASSIVE INSTITUTIONAL CONTROLS

The SNL performance-assessment team began a project in January 1990 to define passive institutional controls for protecting the repository after active control ceases. Because preserving records for 10,000 years will be difficult, permanent physical markers above the repository have been selected as the most effective passive control.

Previous studies on communicating with future societies have been reviewed. Among others, the Office of Nuclear Waste Isolation (ONWI) and Rockwell Hanford Operations have conducted studies on ways to mark storage sites (e.g., Human Interference Task Force, 1984; Adams and Kaplan, 1986). These studies considered not only the longevity of monuments and markers of past societies, but also examined attempts by present-day societies to communicate with others (for example, National Aeronautics and Space Administration's "greeting cards" carried on the Pioneer and Voyager probes). Work done for the WIPP Project will draw upon the conclusions of these studies. Issues include the physical durability of the markers, with emphasis on materials, size, shape, and resistance to natural and human attack, and the transfer of information, with an emphasis on signs and symbols most likely to remain intelligible to future societies. The performance-assessment team also will use existing numerical models to identify those parameters most likely to affect drilling and its consequences. As discussed in Chapter III, calculations have already demonstrated the importance of effectively resealing an intruding borehole; for example, the marker could transmit WIPP sealing technology to future societies to reduce the consequences of intentional intrusions.

Projecting future societal needs and actions is at best qualitative. The Standard specifically provides for exceptions to quantitative evaluations where qualitative judgments are adequate or the only choice. This expertise is not available within the Project.

A panel of experts qualified to address questions about the probability of intrusion and the effectiveness of marker systems is being assembled. These experts will evaluate the available information, break the problems down into manageable components, and, with the assistance of probability specialists, quantify their subjective conclusions to the greatest extent possible. This methodology for using panels of experts to evaluate complex problems has often been used and does not originate with this project (Hora and Iman, 1989; Bonano et al., 1989). After completion of this task, similar panels will evaluate other important questions relating to the performance assessment.

Experts are being selected from many academic and professional disciplines, with nominations from groups outside the Project and the DOE. Authors of the earlier communication studies are invited to participate. No panel members

have a pre-existing personal or professional stake in the outcome. Panel members are provided with the information assembled by the performance-assessment team, and they are encouraged to add to it. They are also provided with the performance-assessment team's interpretation of the problem and key assumptions. This interpretation is not offered as the "correct interpretation"; it is intended instead to focus debate on the critical issues. Panel members are expected to make their own interpretations.

Experts will receive workshop training in those techniques of probabilistic analysis relevant to performance-assessment work. This is essential because experts on specific topics are not expected to have the background needed to translate their qualitative judgments into the probabilistic terms required for incorporating the results into the CCDF.

Experts' opinions and judgments will be elicited by the performance-assessment team in carefully documented, formal interviews. Experts will be expected to explain their interpretations and the reasoning behind their assumptions. Trained analysts will perform the interviews and assist in quantifying the results. The effectiveness of passive marker systems will be described probabilistically, and used as a basis for estimating drilling probabilities.

THE PROBABILITY OF INTRUSION

Tierney (1990) has identified several questions that define the ways passive markers could affect a future decision to drill. First, are the markers evident? If not, they will have no effect, and the probability of drilling is the same as that for an unmarked site. If the markers are evident, is the message still physically legible? If not, do the drillers proceed, or do they reconsider? If the message is legible, but they cannot understand the message, will they recognize that the marker is telling them something and reconsider or abandon their project? If they do understand the message and drill anyway, the intrusion is deliberate, and consequences are not regulated. If the message conveys information, however, about effective plugging technology, it could enhance the safety of the repository following such a deliberate intrusion.

Assessing the probability of intrusion will require quantitative probabilistic answers to each question. In all cases, probabilities will be time-dependent. Neither drilling activity nor the effectiveness of the markers can be expected to be constant through time. Fundamental to all cases will be a value for the probability that drilling might occur on an unmarked site.

Guzowski (1990b) has outlined possible approaches to estimating drilling probability at an unmarked site. One approach described by Guzowski (1990b) uses

expert opinion as outlined above and will be a factor in any assessment of drilling probability. Ultimately it may prove to be the only useful approach. Regardless of the method used to assign a probability to intrusion, the reasonableness of that probability can be evaluated only by expert judgment.

Guzowski (1990b) also identified a frequentist technique, in which available data are examined to determine the past frequency of drilling and make projections of future drilling rates. Frequentist models would involve the extrapolation of present and past trends into the future, but extrapolating out to 10,000 years from 100 years of history is questionable at best.

Another approach described by Guzowski (1990b) is developing a probability model in which drilling is assumed to be random and all possible responses to any decision have equal probabilities of occurring. At its simplest, this model would determine a probability of drilling at the waste-panel location based on a yes/no decision with all decisions having equal probabilities. Appendix B of the Standard suggests some probability of 30 boreholes per square kilometer per 10,000 years as an upper limit and a nonzero probability of at least one borehole as a lower limit. Drilling at the upper density limit would result in an additional 900,000 boreholes in the Delaware Basin within the next 10,000 years. It would also result in a maximum of 15 penetrations of the 0.5 km² waste-storage area. Each possible number of boreholes could be considered to have the same probability of occurring as any other possible number. Given expectations about the future resource potential of the basin, Guzowski (1990b,c) believes this drilling density is too high.

Guzowski (1990b) suggested that an alternate approach to determining the total number of boreholes would be to project into the future the current drilling density as controlled by state regulations. The State of New Mexico Oil Conservation Division (1989) limits the size of the tract on which exploration boreholes may be drilled in the vicinity of the WIPP to either 40, 160, or 320 acres, depending on projected depth and the nature of the hydrocarbon expected. The most conservative assumptions about the resource target yield a maximum of 9 penetrations of the waste panels; the more likely drilling for deep gas could generate a maximum of only 2 penetrations under present regulations.

More complicated probability models could be constructed by adjusting the total number of boreholes expected in the basin to take into account available information about the future resource potential of the basin. Guzowski (1990c) reasoned that because the hydrocarbon resources of the basin are already largely exploited, drilling after active institutional control ends could be a low-probability event. Expert judgment could evaluate, on both

global and local scales, the geologic and economic factors that will control drilling rates in the distant future.

Tierney (1990, Appendix C) presents a probability model based on an application of the failure-rate function commonly used for statistically predicting time-to-failure for both biological and engineered systems (e.g., Elandt-Johnson and Johnson, 1980; Ross, 1985; Harr, 1987). In general, the function can be integrated to yield the probability that an event will occur in any time interval given that the event has not already occurred. Tierney (1990, Appendix C) proposes using the failure-rate function to construct a distribution function for the time of first intrusion at the WIPP by making assumptions about drilling rates during three separate time intervals: the period of active institutional control when the drilling rate should be zero; a period of undefined duration when passive controls effectively reduce the probability of intrusion; and an equally uncertain period of no predictable control after markers have become totally ineffective.

The method chosen for determining the probability of intrusion will depend on further research into the available data. It will also depend on the judgment elicited from the expert panels being assembled to assess drilling probability and determine criteria for passive markers. The failure-rate function will be used to estimate intrusion probabilities for the December 1990 preliminary performance assessment. Expert panels will participate in selecting the method for future assessments.

V. PROPERTIES OF THE WASTE AND THE ROOM

The total quantity of radionuclides transported from the disposal area by ground water following an intrusion will significantly affect repository performance. This quantity depends in part on the material properties of the waste and the long-term physical characteristics of the disposal rooms. Properties of the brine reservoir that underlies part of the repository, the borehole plug, brine chemistry, and geology of overlying units, which include the Culebra Dolomite Member of the Rustler Formation are not discussed in this chapter. Waste and disposal-room properties include the rate brine flows through the waste, the solubility of radionuclides in the brine, and the total surface area of waste exposed to the brine. These are controlled by one or more room parameters such as the rate brine enters the waste-storage area, gas pressure, porosity and hydraulic conductivity of the waste and backfill, chemical composition of the waste, radionuclide distribution, and the degree to which the rooms within each panel remain interconnected after the repository is sealed.

SENSITIVITY ANALYSES OF ROOM PARAMETERS

The initial probabilistic calculations of repository performance presented by Marietta et al. (1989) conservatively assumed that a large quantity of radionuclides could be transported from the disposal area. Waste was assumed to be placed in the repository in the uncompacted, relatively permeable form currently in storage. No engineered barriers impeded brine flow within the panel containing the breached room (although panel seals were assumed effective), and radionuclides throughout the entire panel were available for long-term transport up a borehole and laterally through the subsurface to the accessible environment. Data on radionuclide solubilities for the WIPP underground environment are scarce, so a pessimistic distribution function was used for radionuclide solubility. Parameter values for this "reference design" case can be found in Appendices B and C of Marietta et al. (1989).

Marietta et al. (1989) recognized that these assumptions might be unnecessarily severe and that changes in specific parameters could significantly alter predictions of repository performance. Simulations using less conservative values for waste porosity and conductivity, corresponding hypothetically to compacted and grouted waste, resulted in a substantial shift in the CCDF curves. Anderson et al. (1990) repeated these simulations using fixed values reflecting "least favorable," "expected," and "most favorable" conditions. "Expected" values of 0.18 for effective porosity and 10^{-6} m/s for conductivity represent the average properties of all waste in the repository

after creep closure (see Lappin et al., 1989, Ch. 4.0, for derivation of these estimates). "Least favorable" values of 0.30 and 10^{-4} m/s for the most porous and least compacted waste and backfill in the repository after creep closure would be applicable only if an entire panel had been loaded with such material. The hypothetical "most favorable" values of 0.05 and 10^{-11} m/s represent waste modified prior to emplacement in the repository and not affected by gases generated after decommissioning. Modifications such as grouting and supercompaction that could produce such initial values are discussed in Chapter VII. The effects of gases and gas pressures on such wastes must be investigated.

As expected, the resulting CCDF curves show that reductions in brine flow through the waste cause significant shifts toward lower cumulative radionuclide releases (Figure 5-1). As with other CCDF curves presented in this report, the EPA Containment Requirement is shown for reference purposes only, and these plots do not establish compliance or noncompliance. The calculations assume the El intrusion occurs, as described in Chapter I, and are intended to show only the sensitivity of the overall performance to specific variations in the parameters controlling fluid flow through the waste. They omit releases that occur at the ground surface during the drilling operation because drilling releases would be constant for all single-intrusion curves; the comparisons are not sensitive to drilling releases. These sensitivity analyses are designed to show the effects of parameter changes on subsurface releases at the boundary of the accessible environment. The technique for analyzing model sensitivity to specific variations fixes a single value for each test parameter in question and varies all other parameter values probabilistically as described in Chapter II.

Improving waste properties from "least favorable" to "expected" conditions reduces cumulative release by roughly one order of magnitude. Improving waste properties to "most favorable" results in a CCDF curve that plots completely off-scale. If "most favorable" properties could be achieved, no significant long-term releases would occur in the subsurface during the 10,000 years following the abandonment of the borehole, even assuming a deteriorated plug; modifications that achieve these properties could improve the subsurface aspect of repository performance by more than six orders of magnitude. Necessity for and costs of such improvements are not yet known.

Similar CCDF curves show the effect of varying radionuclide solubility (Figure 5-2). Values of 10^{-3} M, 10^{-6} M, and 10^{-9} M were chosen for "least favorable," "expected," and "most favorable" solubilities. Details of the calculations and the parameter distributions are contained in Anderson et al. (1990). Research is in progress (Brush, 1990; U.S. DOE 1990b) to determine the range

Figure 5-1. Conditional CCDF curves showing sensitivity to variations in room porosity and hydraulic conductivity (Anderson et al., 1990). "Expected" and "least favorable" values for room porosity and hydraulic conductivity are shown. "Most favorable" values, corresponding to stable, hypothetical super-compacted or grouted waste, plot off-scale. Curves assume intrusion scenario E1 occurs. Curves were calculated using the preliminary modeling system described in Marietta et al. (1989) and cannot be used to judge compliance or noncompliance because all significant scenarios are not included, crucial models and data are missing, surface releases are omitted, and the Standard has been vacated. The curves simply measure modeling sensitivity to variations in the test parameter.

Figure 5-2. Conditional CCDF curves showing sensitivity to variations in radionuclide solubility (Anderson et al., 1990). Curves assume intrusion scenario E1 occurs. Curves were calculated using the preliminary modeling system described in Marietta et al. (1989) and cannot be used to judge compliance or noncompliance because all significant scenarios are not included, crucial models and data are missing, surface releases are omitted, and the Standard has been vacated. The curves simply measure modeling sensitivity to variations in the test parameter.

of values for waste solubility in the WIPP underground environment. As simulated using the assumed values, total radionuclide release varies by nearly three orders of magnitude between the upper and lower extremes. Reductions in radionuclide solubility could result in a significant improvement in performance, but for the assumed scenario, the potential benefit is not as great as that gained by reducing brine flow through the waste.

These two sensitivity analyses indicate that modifications reducing radionuclide dissolution and transport out of the disposal room for the life of the repository could dramatically improve repository performance if such modifications are judged necessary. These modifications are not limited to the specific parameters examined with these calculations. Comparable reductions in release can be achieved through any technique restricting radionuclide transport up the borehole; furthermore, the success of such modifications does not depend on unknown or unpredictable future events. The relative effectiveness of modifications is also not dependent on natural phenomena such as brine-reservoir properties or transport properties of the Culebra Dolomite Member of the Rustler Formation. The absolute positions of the CCDF curves shown here, however, are dependent on these phenomena and the way they are modeled. For example, all calculations presented here assume pressurized brine flow from the Castile Formation is constant for 10,000 years and only fracture flow occurs in the Culebra Dolomite.

Modifications to the waste and the disposal rooms would be made before or during waste emplacement and would use currently available technology. Chapter VII describes modifications presently under consideration and their possible contributions to repository performance. No decision has been made to implement modifications because the necessity for modifications has not been demonstrated. Butcher (1990) conceptualized an alternative to illustrate how initial values similar to the "most favorable" values could be achieved. He suggested that substantial control of porosity and hydraulic conductivity could be achieved over the 10,000 years of regulatory interest (see Chapter VII). Several such alternatives will be evaluated (U.S. DOE, 1990c).

VI. GAS GENERATION WITHIN THE REPOSITORY

Numerically simulating repository performance while explicitly including the effects of gas generated within the waste-storage area will not be possible until 1991. However, the "degraded" values for porosity, permeability, and panel seal efficacy in deterministic (Lappin et al., 1989; U.S. DOE, 1990a) and probabilistic (Marietta et al., 1989; Anderson et al., 1990) analyses reflect possible consequences of gas pressurization.

Transuranic waste can generate gas by anoxic corrosion of metallic waste containers and metallic wastes, microbial decomposition of organic wastes, and radiolysis of brine and organic wastes. At present, potential total gas volume, rates and times at which gas will be generated, rates at which gas will diffuse out of the repository, and effects of any resulting increases in pressure within the repository are understood inadequately for definitive calculations. Research will help answer questions about gas generation and dispersal in the repository (Molecke, 1990a, 1990b; U.S. DOE, 1990b). Available data do permit qualitatively considering possible consequences of gas generation.

For example, gas generation primarily could influence repository performance by raising fluid pressure. Consequences could include maintaining or increasing porosity and permeability within the repository and possibly fracturing panel seals or otherwise reducing their effectiveness. Flow mechanisms could change from one phase (brine only) to two phases (brine plus gas). The rise in fluid pressure will be controlled by the total gas volume, the gas-generation rate, the time-dependent volume available for gas storage within the repository, and the rate gas escapes from the disposal room. Present models conservatively assume the far-field gas permeability of the Salado Formation is zero and all gas must be stored in or near the repository (Lappin et al., 1989).

Potential modifications to the waste form or backfill could alleviate pressurization by controlling gas generation. Slow generation rates could allow gases to move into and along the more permeable interbeds at the gas-generation rate, minimizing pressure increases. Very rapid rates could conceivably allow gas to be safely filtered and vented during the period of active institutional control, thus reducing the effects of later gas generation on the sealed repository.

The volume available for gas storage within the repository will be in part a function of the time when gas generation occurs relative to salt creep closing the rooms. Early gas generation could produce pressures sufficient to halt creep closure and reverse brine inflow. In this case, the volume available to

store gas could be considerably greater than presently assumed at maximum closure without gas and pressurization effects could be less (Lappin et al., 1989).

EFFECTS OF GAS GENERATION IN THE UNDISTURBED STATE

The conceptual model of repository behavior acknowledges gas generation by examining possible bounding conditions. Computational model limitations, however, precluded explicitly considering gas in the preliminary simulations indicating the undisturbed repository will perform as intended (Lappin et al., 1989; Marietta et al., 1989). Iterative simulations of undisturbed performance will include gas generation as data and models become available.

Gas generation is not expected to alter repository performance substantially in the undisturbed state. High gas pressures could keep the repository essentially dry, virtually eliminating radionuclide transport. Cumulative releases calculated for the undisturbed scenario assuming a brine-saturated repository could be therefore provide a conservative upper bound for releases expected from a dry or only partially saturated repository.

This assumption will be valid only if gas pressure does not fracture either the Salado Formation or the repository seals and open new pathways for fluid flow to the accessible environment. Seals are expected to be consolidated by salt creep before gas pressure could impair their performance. Therefore, potential for gas-driven bypass of panel seals should be insignificant. Large-scale fracturing of the Salado Formation is also believed to be improbable. Preliminary modeling of the stress fields around the repository suggests that pressures resulting from conservatively high gas-generation rates and volumes will not result in fracturing (Butcher, 1989). Research will continue to examine this question in detail.

EFFECTS OF GAS GENERATION IN THE EVENT OF AN INTRUSION

Elevated gas pressures within the repository could significantly affect the consequences of borehole intrusion. The following discussion (Butcher, 1989) assumes a fully pressurized, nearly dry room is intruded. The El scenario is assumed as described in Chapter I, with drilling continuing through the repository and into a pressurized brine reservoir in the underlying Castile Formation.

The first warning drillers will have of the intrusion will be a pressure "kick" raising the level of the drilling fluid. Drillers for oil and gas in the Delaware Basin, as in most areas, are well-prepared for penetrating

pressurized formations. Drillers reduce pressure by bleeding off gas at the surface and control pressure by increasing the weight of the drilling fluid.

As pressures equilibrate, the drillers could lose circulating fluid into the repository. Lost-circulation problems are not unexpected in drilling operations in the Delaware Basin and are usually controlled by sealing or isolating the porous zone. It is reasonable to assume, therefore, that the drillers will stop drilling fluid from circulating through the repository and will continue drilling toward the target below.

Radionuclide releases could occur by two pathways as discussed in Chapter III. First, some waste will be carried immediately to the surface in the cuttings (or core, if the hole is cored), and waste eroded from the borehole walls will also be carried to the surface by the circulating drilling fluid. Second, pressure gradients could later cause radionuclides dissolved in brine to migrate up the borehole, through degraded plugs, and out laterally through the Culebra Dolomite Member of the Rustler Formation or other units. Gas pressurization could influence releases along both pathways.

Short-term releases at the surface potentially could be increased by the effects of pressurization. If research shows this to be a significant possibility, modifications will be available to increase the shear strength of the waste and minimize the amount of material eroded from the borehole walls (U.S. DOE 1990b).

Long-term transport of dissolved radionuclides into the Culebra Dolomite Member after the borehole has been abandoned could be greater than predicted by gas-free calculations. Until gas generation ceases, elevated pressures could drive additional brine through the waste and up the borehole. Alternatively, 10,000-year cumulative releases could be lower than predicted if borehole plugs are effective and the repository repressurizes sufficiently to reduce brine inflow and radionuclide transport.

Future performance assessments will incorporate gas volumes and gas-generation and dispersal rates. Gas-generation tests with transuranic wastes are planned; these tests will evaluate as-received and reprocessed wastes to determine their suitability for disposal in the WIPP (U.S. DOE, 1990b; Molecke, 1990a, 1990b). Two conservative assumptions underlie the test plans: gas volumes are predicted to be greater than could be stored at "final state" within the repository; and the Salado Formation, including interbeds, is considered impermeable in the far-field at pressures below lithostatic. These assumptions, believed to minimize gas acceptability, will be re-evaluated as results are obtained.

VII. ENGINEERED MODIFICATIONS TO WASTE AND REPOSITORY

Performance of the repository as presently designed is expected to be acceptable. If ongoing research does not establish sufficient confidence in acceptable performance or if it indicates a potential for unacceptable performance, changes in repository design or the waste form could be required. SNL has conducted preliminary research on possible modifications (Butcher, 1990). The Engineered Alternatives Task Force (EATF), assembled by International Technology Corporation for Westinghouse Electric Corporation, the Management and Operating Contractor for the WIPP Project, will identify specific alternatives, rank alternatives according to specific feasibility criteria, and recommend further research (Westinghouse Electric Corporation, 1990; U.S. DOE, 1990c). The EATF has preliminarily identified several alternatives to be tested during the Test Phase (DOE, 1990c). Feasibility criteria include availability of technology, regulatory and institutional constraints, cost and scheduling, and safety. The DOE will make decisions about testing and, if necessary, implementing alternatives based on the recommendations of the EATF and performance-assessment considerations provided by SNL.

This chapter reviews ways in which modifications could improve performance and summarizes the preliminary recommendations of the EATF (U.S. DOE, 1990c). Modifications described here are still being researched, and specific recommendations would be premature. The purpose of this chapter is to indicate the scope of the investigation and to provide an understanding of the range of options that will be available if needed.

POTENTIAL BENEFITS

Modifications could improve repository performance in at least three ways: (1) reduce brine flow through the waste and thereby reduce the rate of radionuclide transport through the disposal room and into an intruding borehole, (2) increase sorption or decrease effective radionuclide solubility within the backfill, and (3) control gas-generation rates or total gas-generation potential, or both (Butcher, 1990). Modifications could be made to the form of the waste or the design of the room.

Butcher (1990) catalogued modifications ranging in complexity and feasibility from simple changes such as altering the backfill to major undertakings such as draining any and all Castile Formation brine reservoirs below the repository. Butcher (1990) did not evaluate modifications except in a preliminary way; the purpose of that SNL effort was to provide early information

for performance-assessment work. A goal was to determine whether modifications could be designed sufficient to provide improvements in simulated performance comparable to those predicted by the sensitivity analyses reviewed in Chapter V and by the *FSEIS* (U.S. DOE, 1990b). Evaluations of specific alternatives will be conducted by the EATF before recommendations are made for detailed evaluation and testing.

AN EXAMPLE MODIFICATION

Based on the SNL investigation, it is possible to conclude that substantial improvements in repository performance are achievable. Butcher (1990) examined a specific set of modifications as an example of a possible way to provide reductions in radionuclide releases during and following intrusion. This example is reviewed here to demonstrate that optimistic predictions of reductions in radionuclide releases are not unrealistic. Calculations presented by Lappin et al. (1989) and Marietta et al. (1989) put potential benefits in perspective. Reductions in initial room permeability of four to five orders of magnitude resulted in calculated radiation doses well below normal background levels (U.S. DOE, 1990a) and cumulative radionuclide releases well within the probabilistic limits set by the Standard.

Butcher (1990) suggests that these reductions in permeability could be achieved by clustering waste containers into "seven-packs," with six containers arranged in a hexagonal ring around a seventh. Waste would be grouted, supercompacted, or otherwise processed before emplacement to reduce void space within containers. The seven-packs would be placed on pads of relatively impermeable bentonite or grout and separated by 6- to 12-inch grout-filled gaps. Copper sulfate could be placed between the pad and the seven-packs if testing demonstrates its effectiveness in reducing the generation of hydrogen gas. Gaps between and above seven-packs would also be grouted, and each seven-pack would be effectively surrounded by a barrier less permeable than the waste within the drums. Remaining space within the disposal rooms would be backfilled with either crushed salt or a mixture of salt and bentonite.

These modifications could greatly reduce long-term brine flow through the waste, thereby reducing the potential for radionuclide transport following intrusion. The modifications could also increase the shear strength of the waste, reducing the amount that could be eroded and brought directly to the surface by circulating drilling fluid in an intruding borehole. The modifications could reduce gas-generation rates and volumes sufficiently so that dispersal along interbeds could prevent significant overpressurization of the repository.

Initial reductions in room permeability resulting from this modification would be comparable to those simulated by Lappin et al. (1989) and Marietta et al. (1989). Long-term performance could be less effective, depending on degradation of the grout with time. Assessments of this modification, and any other similar plan that relies on cement-based grout to reduce permeability, will require an improved understanding of the long-term stability of grouts in the WIPP underground environment. The EATF has convened a multidisciplinary panel to examine the chemical and structural stability of cement and grout over long periods of time (Drez, 1990).

MODIFICATIONS BEING EVALUATED BY THE EATF

Recommendations of the EATF summarized here have been presented in a preliminary form only and are based on qualitative judgment of a multidisciplinary panel (U.S. DOE, 1990c). Final recommendations will be made in early 1991, following data acquisition and development of models adequate to quantify responses to modifications (Westinghouse Electric Corporation, 1990).

The EATF initially considered six categories of potential engineered alternatives: waste forms, backfills, waste management, repository design, passive markers, and miscellaneous. Preliminary work has considered waste forms (or treatments) and backfills only. The relative effectiveness of the alternatives considered was judged against the five major parameters for which engineered changes are both feasible and likely to improve repository performance: radiolytic gas generation, corrosion gas generation, biological gas generation, waste permeability, and radionuclide solubility. These five "performance parameters" were selected by the SNL performance-assessment team from an initial list of ten that also included waste porosity, waste shear strength, waste leachability, brine inflow, and the probability of human intrusion.

WASTE FORM TREATMENTS RECOMMENDED BY THE EATF FOR TESTING

The EATF has recommended fifteen possible waste-form treatments for inclusion in the WIPP experimental program (U.S. DOE, 1990c). These treatments are the highest ranked (most effective) alternatives of those considered. The impacts and benefits of these treatments is being assessed.

Waste-form treatments are classified according to the final waste form rather than by the treatment process to lessen the chance that problems associated with specific treatment processes might lead to the omission of a potentially desirable waste form. The fifteen options consist of six basic waste forms and nine additional variations.

A description of the waste forms evaluated and recommended by the EATF and how they apply to the three initial waste types (sludges, combustibles, and glasses/metals) follows.

Glassified (vitrified) waste. This alternative allows the transuranic nuclides to be solidified in a glass matrix. Sludges could be melted by means of microwave or Joule heating, combustibles could be incinerated and glassified, and metals could be melted and disposed of as low-level waste with radionuclides partitioned during the melting process incorporated into a glassified residue.

The EATF has grouped two waste forms under glassified (vitrified) waste: vitrified combustibles and vitrified sludges.

Cemented waste. Sludges could be mixed with cement to form a cemented monolith with a relatively high pH, which could limit radionuclide solubility and reduce the rate of biological and corrosion processes. Cementing also may reduce the permeability of the sludges, thereby reducing brine flow through the waste. Combustibles could be either shredded or incinerated prior to cementation. Shredding and cementing would slow production of biological gas; incinerating and cementing would essentially eliminate it. Metals could be shredded before cementing to create a waste form with a small void volume. The cement would reduce brine flow through the waste and raise pH (increase alkalinity), thus slowing gas generation from metal corrosion.

The EATF has grouped four waste forms under cemented waste: shredded and cemented combustibles, shredded and cemented metals and glasses, incinerated and cemented combustibles, and cemented sludges.

Compacted waste. Combustibles could be compacted as-is, shredded and compacted, or shredded and mixed with salt before compaction to fill voids that would otherwise remain open. Metals usually cannot be effectively compacted; however, shredding metal and mixing it with salt before compaction has been judged reasonably effective for reducing waste permeability. Sludges cannot be effectively compacted.

The EATF has grouped four waste forms under compacted waste: compacted combustibles, shredded and compacted metals and glasses, and combustibles or metals and glasses that have been shredded, mixed with salt, and compacted.

Shredded waste with bentonite filler. Adding bentonite to combustibles or metals and glasses should decrease their permeability. Bentonite, because it would isolate the metals from the waste room environment, should also

reduce metal corrosion rates. Bentonite could also absorb excess brine. There are no apparent advantages to adding bentonite to sludges.

Metal waste melted into ingots. Melting metal wastes into ingots would decrease the permeability of metal. This process would slow gas generation by corrosion but would not reduce total potential. Conventional means or a plasma furnace could melt the metals. If the temperature of the melt is high enough, radionuclides will preferentially partition into a slag phase, leaving the bulk metal as a low-level waste. The slag residue would be treated separately as transuranic waste, either by cementing or glassification.

pH-buffered waste packages. pH-buffering materials such as activated alumina or lime could be added to sludges, combustibles, and metals to increase the pH in the waste and significantly slow biological and corrosion gas generation. If enough of this material is added (e.g., in the form of portland cement), then brine flow through the waste would also be reduced, and the water that does enter the waste-storage area would partially react with the lime. The high pH could also decrease radionuclide solubility.

The EATF has grouped three waste forms under pH-buffered packages: waste that has been pH-buffered with lime, waste that has been pH-buffered with alumina, and waste that has been pH-buffered with cement.

The EATF eliminated encapsulated waste from consideration for further testing. Encapsulation would solidify combustible and metal wastes in a polymer or bitumen to reduce permeability. By isolating metals from the waste room environment, encapsulation would also reduce corrosion. Because organic polymers and bitumen could increase biological and radiolytic gas generation, this waste form alternative is not recommended. Encapsulation of sludges is not considered effective.

BACKFILLS RECOMMENDED BY THE EATF FOR TESTING

A summary of the backfill alternatives follows. The EATF considered all backfill alternatives except bitumen suitable for further testing. Bitumen was not recommended for use as a backfill because of its potential to provide an additional source of gas and handling concerns.

Cement/grout backfill. Such a backfill is advantageous because it is a semi-liquid material that can flow between waste containers before hardening to a low-permeability solid; however, cementitious grout's potentially poor stability in a salt/brine environment could be disadvantageous unless room closure stabilizes the entire waste and cement/grout monolith.

Salt backfill with pH-buffers added. Adding pH-buffering materials such as activated alumina, lime, or cement to the salt backfill could slow biological and corrosion gas generation significantly. The higher pH could also decrease radionuclide solubility. Reaction between brine and the alumina or lime should decrease the water content.

Salt backfill with brine absorbents. Sorbents such as bentonite added to the salt backfill could effectively absorb water from the brine in the waste room. These sorbents could also be effective in reducing the mobility of radionuclides.

SUMMARY

Studies have identified alternatives that, if required, could improve repository performance. Modifications reducing the availability of radionuclides for transport out of the repository and alleviating potential problems of gas pressurization are being examined. Modifications vary in complexity from relatively simple options, such as grouting the waste, to major undertakings, such as redesigning the repository or vitrifying the waste prior to emplacement. Present research is directed toward identifying the most promising modifications to waste form and backfill so that testing of those systems can begin. Criteria that will be considered in the selection of modifications for testing will include effectiveness, safety, technical and operational feasibility, cost, scheduling, and regulatory constraints.

VIII. CONCLUSIONS

Subpart B of the Standard states that compliance will be based on a "reasonable expectation" of acceptable performance (§ 191.13[b], § 191.15, § 191.6[a]). Based on the 1985 Standard and present understanding of the disposal system, Sandia National Laboratories is confident that a reasonable expectation of acceptable performance can be achieved for the WIPP. It is not possible, however, for the DOE to formally determine regulatory compliance at this time. The 1985 Standard is undergoing revision following remand by a Federal Court of Appeals, and presently available data and models are insufficient for full-scale performance assessments. The term "reasonable expectation" must also be defined more precisely before regulatory compliance is formally established.

Because it is not possible to prove the validity of predictions about future human actions or natural events, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed judgment. The goal of the WIPP performance-assessment team at SNL is to provide as detailed and thorough a basis as practical for that decision. Performance-assessment work will provide quantitative, probabilistic analyses of repository performance, supplemented by expert judgments, for comparison with the regulatory limits.

Work done to date indicates compliance should be expected for undisturbed performance of the repository as presently designed over the 1,000 years defined by the original, vacated Standard. Research will continue to examine undisturbed performance carefully, but it is not considered likely that new data will change the conclusion that the WIPP will comply with the Individual Protection Requirements (§ 191.15).

Currently, compliance with the Ground Water Protection Requirements (§ 191.16) is irrelevant because there is no "special source of ground water," as defined by the vacated Standard, at the WIPP.

Questions remain about the performance of the repository as now designed if inadvertent human intrusion occurs. These include uncertainties about the amount of radionuclides removed by intrusion, the probability of intrusion, the effectiveness of passive institutional controls in lowering that likelihood, and the possible effectiveness of efforts to reseal the repository after the intrusion. Work done to date indicates that even if intrusion occurs, the repository as currently designed is likely to comply with the Containment Requirements (§ 191.13) for the 10,000-year period regulated by the vacated Standard unless conditions controlling radionuclide transport are less

favorable than expected. Preliminary calculations indicate, however, that if several unfavorable circumstances coincide, compliance could be difficult to demonstrate numerically. Performance-assessment work has therefore concentrated on better quantifying these circumstances and establishing reasonable probabilities for their occurrence. Regardless of its likelihood, human intrusion has come to dominate analyses of future performance for the WIPP, overshadowing the otherwise excellent geologic reasons for selecting the site.

The SNL performance-assessment team has identified three pathways for achieving compliance. Each of these three is being researched separately, and each independently has the potential to assure acceptable performance. Results of research and testing are not yet available, and it is therefore not possible to determine at this time what combination of these pathways will be appropriate or required for implementation. It is reasonable to predict at this time, however, that options provided by these pathways will be sufficient to achieve compliance.

The first pathway is completing research on the performance of the repository as presently designed. The computational models and the database used for preliminary calculations are incomplete; therefore, they are not sufficient for predictions. The WIPP Test Phase (U.S. DOE, 1990b) will generate the data needed to improve the quality of performance assessments. Because preliminary assessments relied on conservative and pessimistic assumptions about numerous aspects of performance, it is anticipated that better data and improved models will show some reduction in predicted radionuclide releases following inadvertent human intrusion. The magnitude of this improvement cannot be determined in advance of research, and work is proceeding concurrently on the other two paths.

The second path is to examine the current assumptions about inadvertent human intrusion and evaluate ways to mitigate the consequences through the use of passive markers above the repository. Preliminary assessments have assumed that plugs installed in an intruding borehole will deteriorate to be no more effective at reducing fluid flow than rubble or loose debris. The Standard suggests that these pessimistic conditions are the worst case that should be considered, but it may be neither realistic nor appropriate to ignore more optimistic possibilities. Sensitivity analyses presented in Chapter III show that simulations of repository performance are extremely sensitive to the properties of the borehole plug, and if holes are effectively sealed, predicted radionuclide releases will be dramatically reduced.

Preliminary performance assessments have also assumed that intrusion will occur. This may be unduly pessimistic. Passive institutional controls are being designed that will warn would-be intruders and reduce the probability

that the repository will be breached inadvertently. Messages on the markers could convey information instructing intruders on effective means for resealing the repository to prevent additional releases. Panels of experts are being convened to develop design criteria for markers that will remain visible and comprehensible as long into the next 10,000 years as possible and to evaluate potential marker effectiveness for improving repository performance.

The third path being researched is engineering modifications to limit removal of radionuclides during and following an intrusion. Changes that could significantly improve performance could be made either in the form of the waste or the design of repository. For example, sensitivity analyses presented in Chapter V show that if the porosity and hydraulic conductivity of the waste can be reduced, thereby reducing brine flow through the waste and consequently reducing radionuclide transport, predicted long-term radionuclide releases will be substantially smaller. Reductions in porosity and hydraulic conductivity that are within the reach of present technology could result in predicted subsurface radionuclide releases orders of magnitude below allowable limits. Average releases at the surface during drilling could be about six percent of the regulatory limit. Available alternatives for reducing brine flow through the waste range from relatively simple modifications such as altering the surrounding backfill to major undertakings up to and including vitrifying waste before emplacement.

The EATF is identifying and evaluating engineering alternatives for improving performance (U.S. DOE, 1990c). Alternatives will be ranked on the basis of technical and operational feasibility, safety, regulatory and institutional constraints, and cost. Specific alternatives will be recommended for full evaluation during the WIPP Test Phase (U.S. DOE, 1990b). Implementation will be contingent on test results and need: because modifications are costly and will pose some additional safety risks, none will be implemented unless demonstrated to be effective and required to achieve a reasonable expectation of compliance.

Uncertainties about the effects of gas generation within the repository also complicate performance assessments. Gas could be generated by decomposition of organic wastes, metals, and brine. The capacity of the repository and the surrounding rock to store and disperse gas is unknown; if the volume and generation rate exceed storage volume and dispersal rate, the resulting increase in pressure could either degrade or improve repository performance, depending on the details of the models. Current models and data do not permit quantitatively analyzing the consequences of gas generation, and research will obtain data and establish models to determine whether a problem exists (U.S. DOE, 1990b). Simultaneously, modifications are being examined that have the potential to prevent or reduce gas generation or to otherwise alleviate potential pressurization problems (U.S. DOE, 1990c). Many of these

modifications would serve a dual function of limiting gas generation and decreasing porosity and permeability within the disposal rooms.

Modifying the waste and the repository does not depend on future events; therefore, modifications present an appealing solution to the regulatory problems of human intrusion. Should they be required, modifications will be available that will assure compliance even if human intrusion occurs. Disadvantages of this option are that such modifications will be costly in terms of risk and dollars, and some could raise additional regulatory or safety concerns not directly related to WIPP performance. For example, any increase in waste handling will increase worker exposure. The EPA, in developing the 1985 Standard, did not intend for compliance to require significant increases in cost or difficulty, and benefits from improved future repository performance must be carefully balanced against increased present risks to workers and the general public incurred while modifying the current waste forms.

Research along these three paths will provide the information needed for the WIPP to achieve compliance with Subpart B of the Standard. It is not possible at this time to indicate what combination of methods will be used to achieve compliance, but it is possible to conclude with reasonable confidence that ultimate compliance is not in doubt. The question remaining is not whether the WIPP can comply, but rather how it should comply.

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6310	T. O. Hunter	6346	D. E. Munson
6311	A. L. Stevens	6346	E. J. Nowak
6312	G. E. Barr	6346	J. R. Tillerson
6312	F. W. Bingham	6346	T. M. Torres
6313	T. Blejwas	6350	W. C. Luth
6315	P. C. Kaplan	6350	R. L. Hunter
6315	L. E. Shephard	6400	D. J. McCloskey
6316	R. P. Sandoval	6415	J. Campbell
6317	S. Sinnock	6415	R. M. Cranwell
6320	J. E. Stiegler	6415	J. C. Helton
6340	W. D. Weart	6415	R. L. Iman
6340	S. Y. Pickering	6415	M. Tierney
6341	J. M. Covan	6416	E. Bonano
6341	D. P. Garber	6416	M. Piepho
6341	R. D. Klett	6416	M.S.Y. Chu
6341	R. C. Lincoln	6416	C. P. Harlan
6341	Sandia WIPP Central Files (100)	9300	J. E. Powell
6342	D. R. Anderson (200)	9310	J. D. Plimpton
6342	B. L. Baker	9320	M. J. Navratil
6342	S. G. Bertram-Howery (100)	9325	R. L. Rutter
6342	K. Brinster	9325	J. T. McIlmoyle
6342	A. Gilkey	9330	J. O. Kennedy
6342	L. S. Gomez	9333	O. Burchett
6342	W. D. Grant	9333	J. W. Mercer
6342	R. Guzowski	9334	P. D. Seward
6342	W. Harrison	8524	J. A. Wackerly
6342	H. Iuzzolino	3141	S. A. Landenberger (5)
6342	M. G. Marietta	3151	W. I. Klein (3)
6342	A. C. Peterson	3154-1	C. L. Ward (8) for DOE/OSTI
6342	R. P. Rechard		

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