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PRELIMINARY COMPARISON WITH 40 CFR PART 191, SUBPART B FOR THE WASTE ISOLATION PILOT PLANT, DECEMBER 1990

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is planned as the first mined geologic repository for transuranic (TRU) wastes generated by defense programs of the United States Department of Energy (DOE). Before disposing of waste at the WIPP, the DOE must evaluate compliance with the United States Environmental Protection Agency's (EPA) Standard, *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). Sandia National Laboratories (SNL) is evaluating long-term performance against criteria in Subpart B of the Standard. "Performance assessment" as used in this report includes analyses for the Containment Requirements (§ 191.13(a)) and the Individual Protection Requirements (§ 191.15). Because proving predictions about future human actions or natural events is not possible, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed, qualitative judgment. The goal of the WIPP performance-assessment team at SNL is to provide as detailed and thorough a basis as practical for the quantitative aspect of that decision.

This report summarizes SNL's late-1990 understanding of the WIPP Project's ability to evaluate compliance with Subpart B. This preliminary assessment cannot be defensibly compared to the requirements of the Standard to

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interpret whether the WIPP disposal system complies with Subpart B. Defensibility of the compliance evaluation ultimately will be determined primarily by qualitative judgment regarding "reasonable expectations of compliance," assuming that concept is retained by the EPA in repromulgating the vacated Subpart B. Other considerations such as completeness and adequacy of the numerical simulations will also be factors in determining defensibility. Performance assessment must determine the events that can occur, the likelihood of these events, and the consequences of these events. The impacts of uncertainties must be characterized and displayed; however, no single summary measure can adequately display all the information produced in a performance assessment. Adequate documentation is an essential part of a performance assessment.

In lieu of results suitable for comparison with the Standard, this report presents results of sensitivity analyses that address specific uncertainties in the modeling system. All results are preliminary, and are conditional on assumed conceptual models and parameter value distributions. The results show the degree to which some uncertainties in the conceptual models that describe aspects of disposal-system behavior may affect predicted performance. The results also demonstrate the methodology used to assess performance. The reported complementary cumulative distribution functions (CCDFs) are statistical means of families of CCDFs. The modeling system is sensitive to changes in scenario probabilities, and reductions in the probability of intrusion significantly reduce predicted probabilistic cumulative releases. Comparison of clay-lined-fracture and dual-porosity transport models for the dominant water-bearing unit above the repository indicate a significant increase in radionuclide retardation and a consequent reduction in predicted releases with the dual-porosity model. Simulations of a variable number of intrusions show that, for the selected probability model, multiple intrusions do not increase the largest cumulative releases. Simulations of a hypothetical waste modification suggest that for modifications to be effective, waste permeability must be reduced more than four orders of magnitude below the estimated unmodified value to restrict brine flow to an intruding borehole. Simulations of gas generation and the effects gas will have on brine flow and radionuclide transport are not sufficiently advanced to be incorporated in this year's CCDF curves, but preliminary results of one-dimensional simulations are included. Preliminary analyses for the Individual Protection Requirements suggest that no releases will occur; therefore, dose predictions are not likely to be required.

Although disposal-system characterization work has been underway for about 15 years, and much is known about the WIPP, all work necessary to support the performance assessment has not been completed. Most work currently in progress to support the performance assessment is not advanced enough to support a defensible comparison to the Standard because many important modules are in preliminary or intermediate stages of understanding or readiness. The compliance assessment system can be used for sensitivity and uncertainty analyses, and is adequate for preliminary performance studies.

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PREFACE

The United States Department of Energy (DOE) is planning to dispose of transuranic (TRU) wastes generated by defense programs at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. The WIPP Project will assess compliance with the requirements of the United States Environmental Protection Agency's (EPA) Standard, *Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (40 CFR Part 191). Assessing compliance with the long-term performance criteria of Subpart B of the Standard is a cornerstone for successfully implementing a DOE TRU-waste disposal system.

This report (to be referred to as the *1990 Preliminary Comparison*) previews the planned 1994 document, *Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant* (referred to as the *Comparison*). A preliminary version of the 1994 *Comparison*, this report is the first of the three "Annual Preliminary Comparison to the Standard" reports shown on the Summary Schedule for the Test Phase in the *WIPP Test Phase Plan: Performance Assessment* (DOE/WIPP89-011, Rev. 0). The Test Phase schedule and projected budget may change; if so, the schedule for the performance assessment reports will also change. Where data and models are available, the text is a preview of that for 1994. Where work is incomplete, the text is preliminary. This report is a preview only to the extent that the Standard, when repromulgated, is the same as the vacated 1985 Standard. This report treats the vacated Subpart B of the Standard as if it were still effective, because DOE and the State of New Mexico have agreed that compliance evaluation will continue on that basis until a new Subpart B is promulgated. The approach to the Standard and resultant methodology reported here do not reflect DOE's current policy toward EPA's efforts to develop a new Subpart B.

The *1990 Preliminary Comparison* is based on the December 1989 *Draft Forecast of the Final Report for the Comparison to 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant* (SAND88-1452). Vertical change bars in the right margins of the *1990 Preliminary Comparison* indicate changes from the text published in the 1989 *Draft Forecast*. Material from the December 1989 *Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant* (SAND89-2027) has been included where relevant. The 1989 *Draft Forecast* was designed to give the DOE and other interested parties an opportunity to help determine the format, scope, and content of the planned annual preliminary comparison reports. The DOE recommended no changes to the report. Therefore, all text from that report still pertinent to the performance assessment is repeated in the *1990 Preliminary Comparison*. A new chapter on the Groundwater Protection Requirements was added in response to an EPA suggestion (Chapter IX). Chapter V was expanded to incorporate topics recommended by the BRWM WIPP Panel and the SNL Peer Review Panel for the performance assessment. The discussions in Chapters X and XI provide a perspective on work remaining; these discussions respond to a suggestion from the BRWM WIPP Panel to identify "issues" in the report.

DOE, as the implementing agency for the WIPP under the Standard, is responsible for determining whether the WIPP complies with the Standard. The 1994 document, which will describe the compliance evaluation process and compare the WIPP's performance with Subpart B of the Standard, will be the quantitative basis for DOE's determination. That report will evolve from this and subsequent *Preliminary Comparison* reports planned for 1991 and 1992.

The 1994 *Comparison* will be without precedent as a completed performance evaluation for a geologic repository. Therefore, careful planning is required to assure that the 1994 *Comparison* can be prepared and accepted on time and that it will be adequate to support the determination of compliance and to withstand external challenges. Coordination among the performance assessment team at Sandia National Laboratories; the DOE WIPP Project Office, Albuquerque Operations Office, and Headquarters; the WIPP Panel of the National Research Council's Board on Radioactive Waste Management; the New Mexico Environmental Improvement Division and Environmental Evaluation Group; and the EPA is extremely important prior to preparation of the final *Comparison*, which will start about August 1993.

The draft 1994 *Comparison* will be extensively reviewed prior to final publication. Responding to comments and revising the report will be necessary before the report can be published. The review may conceivably necessitate performing additional analyses and incorporating new data into the 1994 *Comparison*. The review and publication cycle is scheduled to be completed during 1994; the schedule is too tight to allow rescoping and reformatting the *Comparison* at that late date. Therefore, this *1990 Preliminary Comparison* affords interested parties an opportunity to monitor the WIPP performance assessment and assist in scoping the work and the final *Comparison*.

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is planned as the first mined geologic repository for transuranic (TRU) wastes generated by defense programs of the United States Department of Energy (DOE). Before disposing of radioactive waste at the WIPP, the DOE must comply with the United States Environmental Protection Agency's (EPA) Standard, *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). Sandia National Laboratories (SNL), as scientific advisor to the WIPP Project, investigates the salt-bed disposal of TRU wastes, characterizes the site, performs analyses, designs engineered barriers, conducts in situ tests, and evaluates compliance with the long-term performance criteria in Subpart B of the Standard.

Performance assessment as defined for the Containment Requirements (§ 191.13(a)) in the Standard means an analysis that identifies the processes and events that might affect the disposal system, examines the effects of these processes and events on the performance of the disposal system, and estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events (§ 191.12(q)). Performance assessment as used in this report includes the EPA definition as well as analyses for the Individual Protection Requirements (§ 191.15), because the methodology developed for predicting releases is necessary for predicting doses.

Because proving the validity of predictions about future human actions or natural events is not possible, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed, qualitative judgment. The goal of the WIPP performance-assessment team at SNL is to provide as detailed and thorough a basis as practical for the quantitative aspect of that decision. Performance-assessment work at SNL will provide quantitative, probabilistic analyses of disposal-system performance for comparison with the regulatory limits. The SNL performance-assessment team recognizes that the fundamental premise of the EPA Standard is establishing a <u>reasonable expectation</u> of satisfying the quantitative limits. The qualitative nature of the EPA's approach to reasonable expectation is established in § 191.13(b) of the Standard. SNL anticipates that the DOE ultimately will perform the necessary qualitative evaluations to determine whether a reasonable expectation of compliance exists for the WIPP.

This report summarizes SNL's late-1990 understanding of the WIPP Project s ability to quantitatively evaluate compliance with the long-term performance requirements set by Subpart B of the Standard. This preliminary assessment cannot be defensibly compared to the requirements of the Standard to interpret whether the WIPP disposal system complies with Subpart B. The disposal system is not yet adequately characterized, and necessary conceptual models, computer programs, and data bases are still incomplete; furthermore, Subpart B of the EPA Standard was vacated in 1987 and remanded to the EPA for reconsideration. Instead, this report examines whether the information available is adequate for producing a defensible comparison with Subpart B of the 1985 Standard, in keeping with the DOE Consultation and Cooperation Agreement (as amended) with the State of New Mexico. Defensibility of the compliance evaluation ultimately will be determined primarily by qualitative judgment regarding reasonable expectations of compliance, assuming that concept is retained by the EPA in repromulgating Subpart B. Other considerations such as completeness and adequacy of the numerical simulations for the performance assessment will also be factors in that determination.

Philosophy

The WIPP performance assessment is based on four ideas. First, a performance assessment must determine the events that can occur, the likelihood of these events, and the consequences of these events. Second, as uncertainties will always exist in the results of a performance assessment, the impact of these uncertainties must be characterized and displayed. Thus, uncertainty analysis and sensitivity analysis are important parts of a performance assessment and dominate the calculations. Uncertainty analysis determines how imprecise knowledge about the disposal system affects our confidence in the results of the consequence analysis. Sensitivity analysis determines the importance of specific components or subsystems to the results of the consequence analyses. Third, no single summary measure can adequately display all the information produced in a performance assessment. Thus, decisions on the acceptability of the WIPP must be based on a careful consideration of all available information rather than on a single summary measure. Fourth, adequate documentation and independent peer review are essential parts of a performance assessment, without which informed judgments on the suitability of WIPP as a waste repository are not possible. An extensive effort is being devoted to documenting and peer reviewing the WIPP performance assessment and the supporting research, including techniques, models, data, and analyses.

Results

In lieu of results suitable for comparison with § 191.13(a) of the Standard, Chapter VI contains the results of sensitivity analyses that address specific uncertainties in the modeling system. All results are preliminary, and are conditional on assumed conceptual models and parameter value distributions. The results show the degree to which some uncertainties in the conceptual models that describe aspects of disposal-system behavior may affect predicted performance. The results also demonstrate the methodology used to assess performance. Each reported complementary cumulative distribution function (CCDF) is the statistical mean of a family of CCDFs. In each case, the mean CCDF predicts probabilistic releases within EPA limits. The significance of these predictions cannot be interpreted for comparison with the Standard.

Mean CCDF curves are presented for analyses of modeling-system sensitivity *ceteris paribus* to the assignment of scenario probabilities, the choice of conceptual model for radionuclide transport in the Culebra Dolomite, and the occurrence of multiple intrusions by exploratory boreholes. Mean CCDF curves also examine sensitivity *ceteris paribus* of the modeling system to a hypothetical modification to the waste form which reduces porosity and permeability and increases shear strength.

Results indicate that the modeling system is sensitive to changes in scenario probabilities, and that reductions in the probability of intrusion do significantly reduce predicted probabilistic cumulative releases. Comparison of clay-lined-fracture and dual-porosity transport models indicate a significant increase in radionuclide retardation and a consequent reduction in predicted releases with the dual-porosity model. For the assumed models and parameter value distributions, dual-porosity retardation reduces long-term subsurface releases sufficiently so that releases at the ground surface during drilling dominate the greater-probability portion of the mean CCDF curve.

Results of simulations using an arbitrary Poisson distribution for the number of future intrusions, rather than the assigned probabilities used in other simulations, indicate that, for the assumed distribution, probabilities of some releases are increased, but total cumulative releases for all probabilities are slightly reduced. Increases in some release probabilities correspond to a greater number of intrusions. Overall reduction in low-probability cumulative releases reflects the abandonment of arbitrary assumptions used to define the fixed-probability E1E2 scenario. Although the number of intrusions increases, two intrusions never occur simultaneously, and borehole plugs are not defined so as to divert all brine flow from the Castile Formation through the waste.

Comparison of results from simulations with and without hypothetical waste modifications suggest that for modifications to be effective, waste permeability must be reduced sufficiently to restrict brine flow to the intruding borehole. Current modeling of brine flow into the repository indicates that reducing waste permeability more than four orders of magnitude below the estimated unmodified value will effectively limit brine flow through the waste and thereby reduce radionuclide transport. Without waste-form modification, brine flow through the waste will be limited primarily by the permeability of the Salado Formation and the rate at which brine seeps into the repository.

None of the mean CCDF curves incorporates effects of climatic change, possible subsidence related to potash mining in the region, or gas generation within the waste. Work in progress suggests that, in the absence of some mechanism for increasing leakage locally into the Culebra Dolomite, climatic change will not have a major impact on the disposal system. Subsidence due to potash mining is believed to be a low-probability event that will have little impact on local groundwater flow and radionuclide transport, but sensitivity analyses will determine whether this additional event is included in the 1991 performance assessment.

Simulations of gas generation and the effects gas will have on brine flow and radionuclide transport are not sufficiently advanced to be included in producing mean CCDF curves, but preliminary results of two-dimensional undisturbed and one-dimensional post-intrusion simulations are included in this assessment. These simulations indicate that gas pressure will be sufficient in the undisturbed state to drive most brine from the upper portion of the waste, preventing significant radionuclide dissolution and transport within the gas-saturated zone. As simulated, essentially no gas migrates into the intact halite of the Salado Formation. Gas does migrate away from the repository, however, through underlying and overlying higher-permeability layers (Marker Bed 139 and anhydrite layers A and B). Simulated gas saturation levels in these layers drop off sharply between one and two kilometers from the repository. If intrusion occurs, and if the permeability of the anhydrite layers is at the low end of the expected range, gas saturation within the room will remain high enough to retard radionuclide transport up the borehole for at least 10,000 years. At higher anhydrite permeabilities, capillary pressure within the anhydrite layers and the rate of gas generation will control brine flow through the waste and radionuclide transport up the borehole.

Gas-generation effects will be incorporated more fully in subsequent assessments when a two-dimensional version of the two-phase flow program is verified and available for use. Future simulations will improve coupling of the processes of gas generation, brine flow, and salt creep. Gas generation consumes water, and generation rates will decrease as gas saturation increases. Permeability in the anhydrite layers could increase as pre-existing fractures open under increased pressure.

Status

The performance assessment must build on computational bases from components to subsystems and finally to the total system. Although disposal-system characterization work has been underway for about 15 years, all work necessary to support the performance assessment has not been completed; some of this work has only recently been initiated. The computational bases currently being developed for the natural barrier systems and the repository and shaft systems were examined for completeness, and qualified as "preliminary," "intermediate," or advanced." Much of the research and experimental work now underway has not been evaluated with sensitivity analyses to determine importance of the work to performance assessment of the total system; therefore, all components and subsystems now being investigated are assumed to be equally necessary. In many cases, our understanding of the component or subsystem being investigated is intuitive and incomplete, and data acquisition, modeling, or computer programming is only planned or recently initiated. Such work is considered to be in a preliminary stage. Other work is considered to be in an intermediate stage because important processes are identified and understood. Elements of the compliance assessment system are qualified as intermediate when some site-specific data are available but data adequacy is unclear, or models and computer programs are being developed, or both, and importance of the component or subsystem to performance assessment is not fully known. Work is considered to be advanced if the importance of the component or subsystem has been determined by sensitivity analyses, uncertainty in the conceptual models for the component or subsystem is adequately understood, the data base is adequate for performance assessments, and the models and computer programs are ready. Much of the work currently in progress to support the performance assessment is in the preliminary stage, and virtually none of the current work is considered advanced enough to support a defensible comparison to the Standard.

Conclusions

Conclusions that can be drawn for each of the requirements in the 1985 Standard are:

- **Containment Requirements.** The compliance assessment system can be used for sensitivity and uncertainty analyses, and is adequate for preliminary performance studies. The computational bases for the compliance assessment system are inadequate at this stage for a defensible comparison to the 1985 Standard, because many important modules are in preliminary or intermediate stages of understanding or readiness.

- **Individual Protection Requirements.** Because the compliance assessment system must be used to predict releases to the accessible environment for undisturbed performance, a defensible comparison to the Standard cannot be prepared until the bases of the system are judged adequate. Preliminary analyses and related deterministic analyses do suggest that no releases will occur; therefore, dose predictions are not likely to be required.

- **Assurance Requirements.** Plans for implementing the first three Assurance Requirements (Active Institutional Controls, Monitoring, and Passive Institutional Controls) are preliminary. Barrier design is an integral part of the SNL research effort. The WIPP Project has satisfied the Natural Resources and Waste Removal requirements.

- **Groundwater Protection Requirements.** This section of Subpart B is not relevant to the WIPP, because no "special source of groundwater" exists.

I. INTRODUCTION

The text of Chapter I is preceded by a synopsis that simplifies concepts presented in Chapter I. Detailed information about those concepts is in the text following the synopsis.

Synopsis

Purpose of This Report

Before disposing of radionuclides at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy (DOE), the responsible agency, must determine that the WIPP can comply with pertinent regulations. This report considers the regulations set by the Environmental Protection Agency (EPA) as 40 CFR Part 191.

A major activity in determining whether the WIPP will provide safe disposal of radionuclides is comparing the predicted long-term performance of the WIPP disposal system to this EPA regulation (called the Standard in this report).

This 1990 report is a preliminary version of a planned 1994 final document and contains the first preliminary assessment of predicted long-term performance of the WIPP.

Important Terms

accessible environment—The atmosphere, land surfaces, surface waters, oceans; and the solid portion of the Earth, including the groundwater contained in it, that is beyond the controlled area.

controlled area—The solid portion of the Earth no more than 5 km (3 mi) from the outer boundary of the WIPP waste-emplacement panels, including the surface and any groundwater. The extent of the WIPP controlled area will be defined during assessment of the long-term performance of the disposal system but will not be less than the proposed WIPP withdrawal area.

decommissioning—Actions taken upon abandonment of the repository to reduce potential environmental, health, and safety impacts, including repository sealing as well as activities to stabilize, reduce, or remove radionuclides or to demolish surface structures.

disposal system—Any combination of man-made and natural barriers that isolates the radionuclides after disposal; for the WIPP, these are the repository/shaft system and the geologic and hydrologic systems of the controlled area.

repository/shaft system—The WIPP underground workings including shafts, all emplaced materials, and the altered zones within the bedded salt and overlying rock units resulting from construction of the underground workings.

WIPP withdrawal area—Sixteen contiguous square miles proposed to be withdrawn from public access to be dedicated to disposal of radionuclides.

Contents of the Standard

The 1985 Standard is composed of two subparts and two appendixes. The full text of the Standard is in Appendix A of this report.

Subpart A:

> Applies to a radionuclide disposal facility prior to decommissioning and contains the standards for management and storage of radionuclides.
>
> Sets limits on the amount of radiation from waste management and storage operations that is acceptable for members of the public outside the waste disposal facility.

This report does not discuss the approach chosen for assessing compliance with Subpart A.

Subpart B:

> Applies to a radionuclide disposal facility after it is decommissioned and contains the standards for radionuclide disposal.

Sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal (Containment and Assurance Requirements) and defines qualitative means of increasing confidence in containment (Assurance Requirements).

Sets limits on the amount of radiation that is acceptable for members of the public in the accessible environment within or near the specified controlled area for 1,000 years after disposal (Individual Protection Requirements).

Sets limits on the acceptable amount of radioactive contamination of certain sources of groundwater within or near the controlled area for 1,000 years after disposal (Groundwater Protection Requirements).

This report discusses the approach for evaluating compliance with Subpart B.

Appendix A:

Specifies how to determine release limits.

Appendix B:

Provides non-mandatory guidance for implementing Subpart B.

A "Reasonable Expectation" of Compliance

The three quantitative requirements in Subpart B specify that the disposal system provide a "reasonable expectation" that their quantitative tests can be met.

Because of the uncertainties in long-term projections, absolute proof of compliance with these requirements is not expected or required.

EPA intends the qualitative Assurance Requirements to compensate for uncertainties in projecting the future performance of the disposal system over a period of 10,000 years.

Status of the Standard

The U.S. Court of Appeals has vacated Subpart B of the Standard and remanded it to the EPA for clarification.

The WIPP Project has agreed to continue evaluating compliance with the original Standard until a revised Standard is available.

The Purpose of the WIPP Project

The WIPP is a full-scale pilot plant for demonstrating the safe management, storage, and disposal of defense-generated, radioactive, transuranic waste.

The long-term performance of the WIPP is being predicted. This assessment will help the DOE determine if the WIPP will isolate wastes from the accessible environment sufficiently well to satisfy the disposal requirements in Subpart B of the Standard.

Upon completion of the performance assessment, the decision will be made on whether the WIPP will become a disposal facility. The DOE will apply Subpart A of the Standard to the WIPP beginning with the first receipt of radionuclides.

Participants in the WIPP Project

The DOE has overall responsibility for implementing the WIPP Project. The DOE Albuquerque Operations Office manages the WIPP Project through the DOE WIPP Project Office in Carlsbad, New Mexico.

Westinghouse Electric Corporation (WEC) is the management and operating contractor during the test phase and will be responsible for operations once the decision is made to permanently emplace waste at the WIPP. WEC also implements Subpart A and the Assurance Requirements of Subpart B of the Standard.

Sandia National Laboratories provides necessary scientific investigations for evaluating compliance with the long-term performance criteria in Subpart B of the Standard.

New Mexico and the DOE have an agreement for consultation and cooperation for the WIPP. New Mexico, through the Environmental Improvement Division (EID) and the Environmental Evaluation Group (EEG), has an active part in assuring that public safety issues are fully addressed.

The Board on Radionuclide Waste Management (BRWM) of the National Research Council, the Advisory Committee on Nuclear Facility Safety, the DOE Blue Ribbon Panel, and the Defense Nuclear Facilities Safety Board review the WIPP Project.

The Environmental Protection Agency informally reviews the compliance evaluation.

Physical Setting

The WIPP is in southeastern New Mexico, about 42 km (26 mi) east of Carlsbad, the nearest population center (pop. 27,000).

Less than 30 permanent residents live within a 16-km (10-mi) radius of the WIPP; the nearest residents live about 5.6 km (3.5 mi) south of the WIPP surface facility.

The quality of the well water has always been poor, and water for people and most livestock is supplied by pipeline.

Potash, oil, and gas are the only known important mineral resources in the area; however, resource extraction is not allowed within the proposed land withdrawal boundaries.

The WIPP is in the Delaware Basin in an area of gently rolling hills known as Los Medaños.

The Delaware Basin began forming 450 to 500 million years ago as a broad, low depression. About 250 million years ago, the thick salt beds of the Salado Formation, which hosts the WIPP, and the Castile Formation, an evaporite deposit that underlies the Salado, accumulated in the Delaware Basin.

Minimal tectonic activity has occurred in the region during the past 250 million years. Faulting about 10 million years ago formed the Guadalupe and Delaware Mountains along the western edge of the basin.

The most recent igneous activity in the area was about 35 million years ago; major volcanic activity last occurred over 1 billion years ago. None of these processes affected the Salado Formation in the vicinity of the WIPP.

The Bell Canyon Formation, deposited more than 250 million years ago, is about 2,000 m (1,250 ft) below the WIPP repository and is the deepest hydrostratigraphic unit currently being considered in the performance assessment; exploratory drilling into this formation for oil and gas could penetrate the WIPP.

The Castile Formation, the formation below the rock unit hosting the WIPP, contains pressurized brine that could affect repository performance if breached by an exploratory borehole.

The Salado Formation, the bedded salt that hosts the WIPP, has minimal groundwater movement because the salt lacks primary porosity and open fractures.

Several rock units above the Salado Formation could provide pathways for radionuclide migration away from the WIPP:

> The Rustler-Salado contact residuum, above the salt of the Salado Formation, contains brine. The residuum recharges east of the WIPP and discharges south-southwest at the Pecos River.
>
> Groundwater flow in the Rustler Formation, above the residuum, is restricted mostly to the Culebra Dolomite and Magenta Dolomite Members. Water in the Culebra Dolomite Member contains large amounts of total dissolved solids; recharge is apparently north of the WIPP, and discharge is to the west-southwest. The Magenta Dolomite Member produces only small amounts of water; recharge probably occurs north of the WIPP, and discharge is probably into the lower units.

Currently, units younger than the Rustler Formation are not hydrologically important because they are not extensive and are unsaturated throughout most of the WIPP area. However, climatic changes or a breach of a pressurized reservoir could cause saturation in the future.

The WIPP Repository/Shaft System

The WIPP repository is 655 m (2,150 ft) below the land surface in a bed of salt that is 600 m (2,000 ft) thick.

Groundwater movement in the bedded salt is extremely limited; the repository will remain dry while it is ventilated, but slow seepage of brine trapped in the pores of the salt does occur.

The WIPP underground workings are composed of four shafts connected to a single underground disposal level. The shafts will be sealed upon decommissioning of the WIPP.

The WIPP repository is designed with eight panels (groups) of seven rooms each. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be backfilled and sealed, waste will be placed in the horizontal passageways between the panels and backfilled, and access ways will be sealed from the shafts.

Radionuclides Accepted at the WIPP

The radionuclides for which the WIPP is designed are transuranic, defense-program waste generated by U.S. government activities.

A projected inventory shows that the contaminated waste will typically be composed of laboratory and production trash, including cloth, rubber, polyethylene, paper, wood, metals, glass, filters, resins, graphite, oils, solvents, alcohols, and sludges.

Most of the waste has external dose rates so low that people can handle properly sealed drums and boxes without any special shielding. These drums and boxes will be stacked three high in the waste-storage rooms.

A small portion of the waste has a higher external dose rate and must be remotely handled. Waste canisters will be packaged for handling and transportation in specially shielded casks. Remotely handled waste in canisters will be emplaced in holes drilled into the wall of the rooms.

For disposal at the WIPP, both contact-handled and remotely handled waste must comply with the WIPP *Waste Acceptance Criteria*.

Contents of This Report

Chapter I describes the Standard and the WIPP Project.

Chapter II explains how the Standard applies to the WIPP disposal system.

Chapter III describes the reasons for using the chosen approach for assessing whether the WIPP complies with the Standard and gives an overview of the approach.

Chapter IV identifies and describes the scenarios being used in the compliance assessment.

Chapter V describes the components of the compliance assessment system.

Chapter VI presents the results of the first preliminary performance assessment relative to the Containment Requirements of the Standard.

Chapter VII describes analyses and results relative to the Individual Protection Requirements of the Standard.

Chapter VIII describes plans for implementing the Assurance Requirements of the Standard.

Chapter IX discusses the relevance of the Groundwater Protection Requirements of the Standard to the WIPP.

Chapter X examines the status of the computational bases for the assessment.

Chapter XI contains the recommendations of the Sandia National Laboratories performance-assessment team about additional work necessary for final performance assessment.

Appendix A contains the full text of the 1985 Standard.

Appendix B contains no information because the 1990 data base is published separately.

Appendix C contains computational data for this preliminary assessment.

Appendix D contains official review comments from agencies other than the DOE and responses to those comments concerning the two predecessor reports.

Before disposing of radionuclide waste at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy (DOE) must determine that the WIPP can comply with the United States Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radionuclides* (40 CFR Part 191; U.S. EPA, 1985), referred to herein as the Standard. Comparing the long-term performance of the WIPP disposal system with the quantitative requirements of the Standard will help determine whether the disposal system will provide safe disposal of radionuclides. This report is a preliminary version of the planned 1994 publication, *Comparison with 40 CFR, Part 191, Subpart B, for the Waste Isolation Pilot Plant*, which will be the final report for the performance assessment of the WIPP disposal system. Analyses reported in the *Comparison* will be supplemented by the DOE's qualitative judgments in determining whether to proceed with disposal at the WIPP.

Organization of the Comparison

The organization of this report and of the final *Comparison*, which will evolve from this report, is based on the requirements of the Standard. Within the format of the requirements, the report is organized according to the methodology developed by the performance-assessment team to implement the guidance found in Appendix B to the Standard. This level of organization reflects the program elements described in the DOE management plan for the test phase (U.S. DOE, 1990a; also see Bertram-Howery and Hunter, 1989a).

Because this report is a preliminary version of the final report, many sections are preliminary or incomplete. Brief descriptions of the Standard and the WIPP Project are provided in this chapter. Chapter II discusses application of Subpart B of the Standard to the WIPP disposal system. Chapter III describes the compliance-assessment philosophy of the WIPP Project and provides an overview of the methodology. Chapter IV identifies and describes the scenarios being used in the compliance assessment. Chapter V describes the components of the compliance-assessment system. Chapter VI presents the results of the first preliminary performance assessment relative to the Containment Requirements (§ 191.13) of the Standard. Chapter VII describes analyses and results relative to the Individual Protection Requirements (§ 191.15) of the Standard. Chapter VIII describes plans for implementing the Assurance Requirements (§ 191.14) of the Standard. Chapter IX discusses the relevance of the Groundwater Protection Requirements (§ 191.16) of the Standard to the WIPP. Chapter X considers the adequacy of the computational bases for the assessment. Chapter XI identifies additional work necessary for the final performance assessment. Appendix A contains the full text of the Standard, as promulgated by the EPA in 1985. Appendix B of the final *Comparison* will contain the reference data base for the compliance assessment. Appendix C contains the current computational data base.

Appendix D contains comments from the New Mexico Environmental Improvement Division (EID) and the EPA Office of Radiation Programs on the *Draft Forecast of the Final Report for the Comparison to 40 CFR Part 191, Subpart B for the Waste Isolation Plant* (SAND88-1452) and *Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant* (SAND89-2027), and the performance assessment team's responses to those comments. No guidelines are provided by the EPA for preparing and reviewing compliance assessment reports. The final *Comparison* will be reviewed extensively. The planned organization of the final *Comparison* includes a similar appendix that will present the official comments from reviewers outside the DOE and responses to those comments from the performance-assessment team, analogous to the comment-response section typically provided in decision-basis documents. This appendix (D) will appear in each *Preliminary Comparison*.

This report focuses on Subpart B of 40 CFR Part 191. Compliance with other regulatory requirements and analyses for other purposes, such as safety assessments, are discussed in separate documents. The methodology described here is also used for safety assessments.

40 CFR Part 191, The Standard (1985)

The Standard promulgated in 1985 by the EPA is divided into two subparts (Figure I-1). Subpart A applies to a disposal facility prior to decommissioning and limits annual radiation doses from waste management and storage operations to members of the public in the general environment. Subpart B applies after decommissioning and limits probabilities of cumulative releases of radionuclides to the accessible environment for 10,000 years. Subpart B also limits both radiation doses to members of the public in the accessible environment and radioactive contamination of certain sources of groundwater within or near the controlled area for 1,000 years after disposal. Appendix A of the Standard specifies how to determine release limits, and Appendix B of the Standard provides non-mandatory guidance for implementing Subpart B. Application of the Standard to the WIPP is described in the *Compliance Strategy* (U.S. DOE, 1989a), which discusses the WIPP interpretation of various terms and definitions contained in the 1985 Standard.

The concept of "site" is integral to limits established by Subparts A and B for releases of waste from the repository, both during operation and after closure. "Site" is used differently in the two Subparts; the meaning of "site" at the WIPP for each Subpart is discussed and defined below in the appropriate section. The definitions of "general environment," "controlled area," and "accessible environment," which are also important in assessing compliance with the Standard, depend on the definition of "site." "Site" has also been used generically for many years by the waste-management community (e.g., in the phrases "site characterization" or "site specific"); few uses of the word correspond to either of the EPA's usages (Bertram-Howery and Hunter, 1989b; also see U.S. DOE, 1989a).

SUBPART A

Subpart A limits the radiation doses that may be received by members of the public in the general environment as a result of management and storage of transuranic (TRU) wastes at DOE disposal facilities not regulated by the Nuclear Regulatory Commission (NRC). Subpart A requires that "the combined annual dose equivalent to any member of the public in the general environment resulting from discharges of radioactive material and direct radiation from such management and storage shall not exceed 25 millirems to the whole body or 75 millirems to any critical organ" (§ 191.03(b)). The general environment is the "total terrestrial, atmospheric, and aquatic environments outside sites within which any activity, operation, or process associated with the management and storage of...radioactive waste is conducted" (§ 191.02(o)). The site as defined for Subpart A is "an area contained within the boundary of a location under the effective control of persons

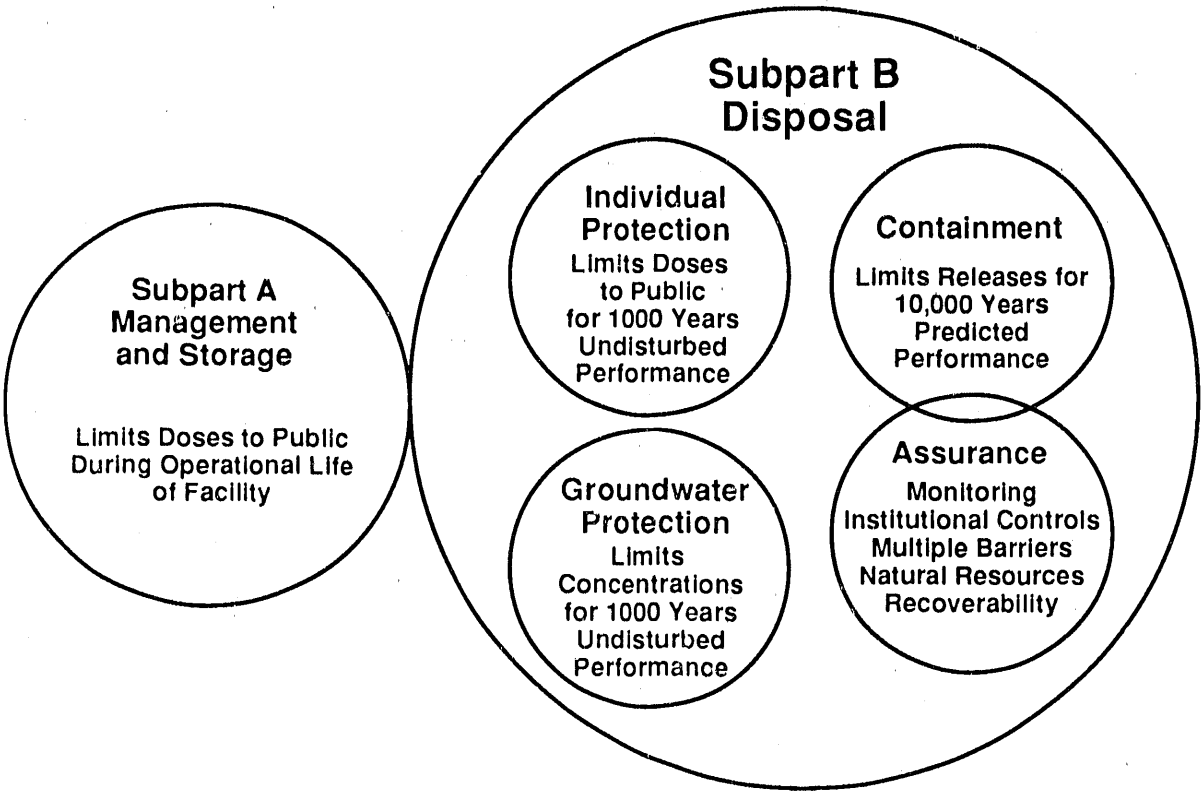

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Figure I-1. 40 CFR Part 191 Environmental Standards for Management and Disposal of Spent Fuel, High-Level, and Transuranic Waste (after U.S. DOE, 1989a).

possessing or using ... radioactive waste that are involved in any activity, operation, or process covered by this Subpart" (§ 191.02(n)).

"Site" for the purposes of Subpart A at the WIPP is the secured-area boundary shown in Figure I-2. This area will be under the effective control of the security force at the WIPP, and only authorized persons will be allowed within the boundary (U.S. DOE, 1989a). In addition, the DOE will gain control over the sixteen-section (16 mi^2) area within the land-withdrawal boundary; this boundary is referred to in the agreement with New Mexico and in the WIPP *Final Safety Analysis Report* (FSAR) (U.S. DOE, 1990b) as the "WIPP site boundary." This control will prohibit habitation within the boundary. Consequently, for the purposes of assessing operational doses to nearby residents, the assumption can be made that no one lives closer than the latter boundary (Bertram-Howery and Hunter, 1989b).

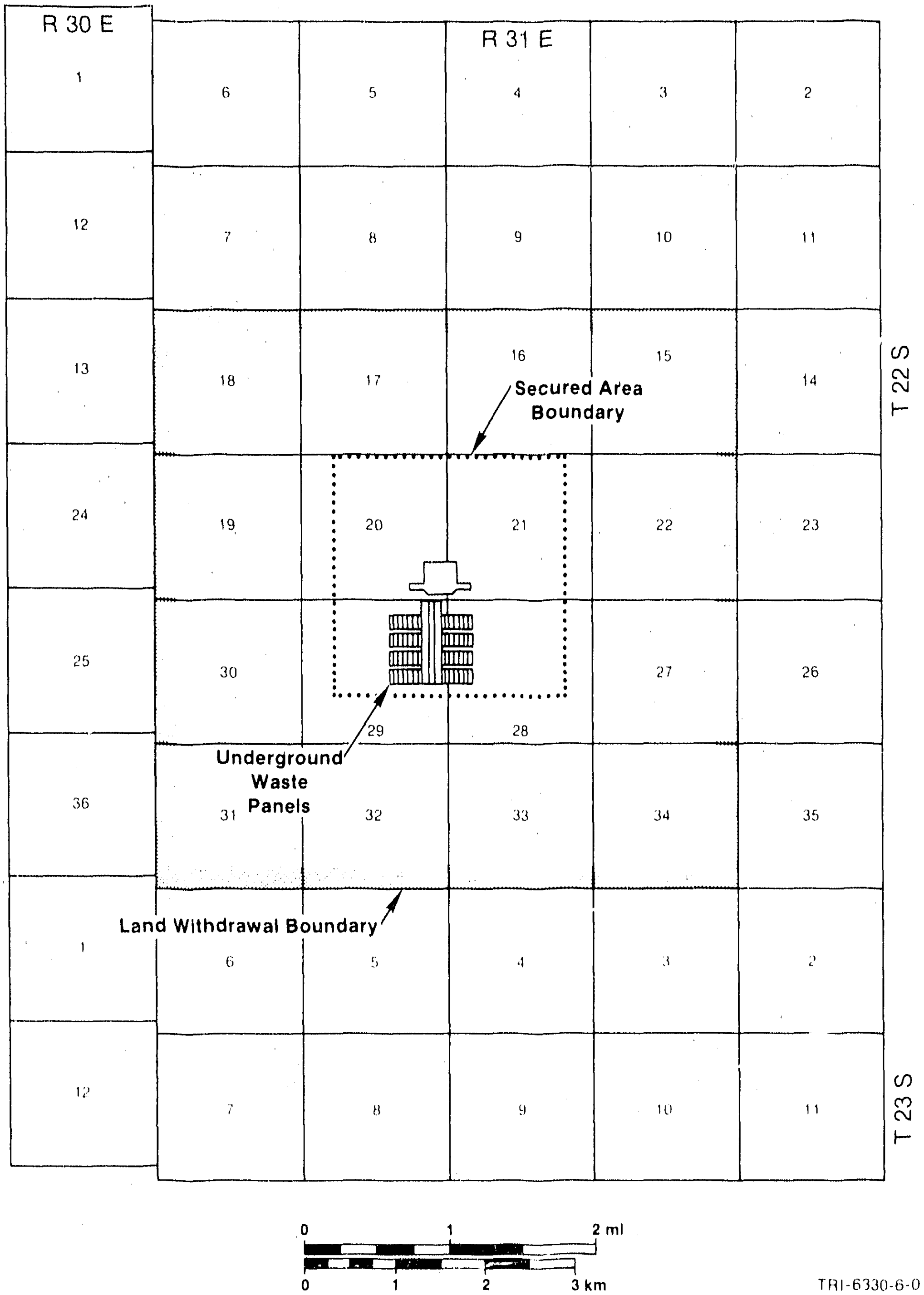
The DOE compliance approach to the Standard is described in the WIPP *Compliance Strategy* (U.S. DOE, 1989a; also see Bertram-Howery and Hunter, 1989b and U.S. DOE, 1990b). Compliance with Subpart B is the topic of this report; therefore, Subpart A will not be discussed further. Discussions contained in this report elaborate on DOE's published strategy (U.S. DOE, 1989a; U.S. DOE, 1990b) for evaluating compliance with the remanded Subpart B. These discussions provide the regulatory framework for the methodology employed.

SUBPART B

In evaluating compliance with Subpart B, the WIPP Project intends to follow to the extent possible the guidance found in Appendix B of the Standard (U.S. DOE, 1989a). The application of Subpart B to the WIPP is discussed in detail in Chapter II. The Containment Requirements (§ 191.13(a)) and Individual Protection Requirements (§ 191.15) necessitate probabilistically predicting cumulative releases for 10,000 years and annual doses for 1,000 years. The Assurance Requirements (§ 191.14) complement the Containment Requirements. The Groundwater Protection Requirements (§ 191.16) limit radionuclide concentrations in specific groundwater sources for 1000 years.

Controlled Area

The controlled area defined by the EPA is limited to the lithosphere and the surface within no more than 5 km (3 mi) from the outer boundary of the WIPP waste-emplacement panels. The boundary of this maximum-allowable controlled area does not coincide with the proposed boundary for the WIPP land withdrawal. The extent of the WIPP controlled area will be defined during performance assessment but will not be less than the area withdrawn, which will be under U.S. Government administrative control (Bertram-Howery and



3 Figure I-2. Position of the WIPP Waste Panels Relative to WIPP Boundaries and Surveyed Section Lines
4 (U.S. DOE, 1989a).

Hunter, 1989a). The accessible environment is "...(1) the atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area" (§ 191.12(k)). The surface of the controlled area is in the accessible environment. The underlying subsurface is not part of the accessible environment. Any radionuclides that reached the surface would be subject to the limits, as would any that reached the lithosphere outside the subsurface portion of the controlled area.

The term "disposal site" is used frequently in Subpart B and in Appendix B of the Standard. For the purposes of the WIPP strategy for compliance with Subpart B, the disposal site and the controlled area are the same. The "site" for the purposes of Subpart A and the "disposal site" for the purposes of Subpart B are not the same (U.S. DOE, 1989a). The Standard defines "disposal system" to mean any combination of engineered and natural barriers that isolate the radioactive waste after disposal. For the WIPP, the disposal system is the combination of the repository/shaft system and the geologic and hydrologic systems of the controlled area (Figure I-3). The repository/shaft system, as defined, includes the WIPP underground workings and all emplaced materials and the altered zones within the Salado Formation and overlying units resulting from construction of the underground workings.

The surface of the controlled area is to be identified by passive institutional controls, which are permanent markers placed at a disposal site, along with records, government ownership, and other methods of preserving knowledge about the disposal system (§ 191.12(g)). The disposal site is to be designated by permanent markers and other passive institutional controls to indicate the dangers of the wastes and their location (§ 191.12(e)).

Reasonable Expectation

The three quantitative requirements in Subpart B specify that the disposal system design must provide a "reasonable expectation" that their various quantitative tests can be met. This test of qualitative judgment is meant by the EPA to "acknowledge the unique considerations likely to be encountered upon implementation of these disposal standards" (U.S. EPA, 1985, p. 38071). The Standard "clearly indicates that comprehensive performance assessments, including estimates of the probabilities of various potential releases whenever meaningful estimates are practicable, are needed to determine compliance with the containment requirements" (U.S. EPA, 1985, p. 38076). These requirements "emphasize that unequivocal proof of compliance is neither expected nor required because of the substantial uncertainties inherent in such long-term projections. Instead, the appropriate test is a reasonable expectation of compliance based upon practically obtainable information and analysis" (ibid.). The EPA states that the Standard requires "very stringent

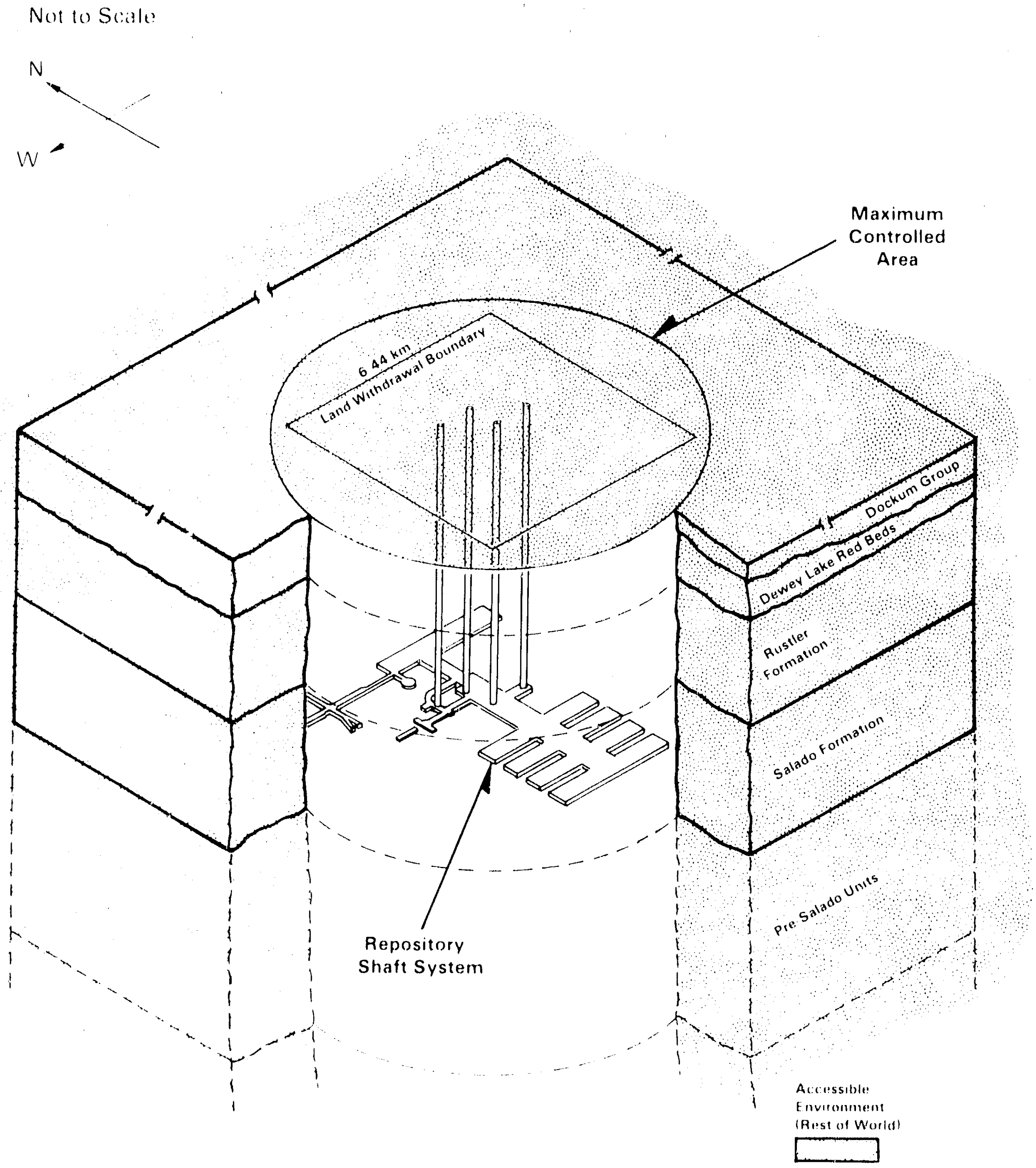


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Figure I-3. Artist's Concept Showing the Two Components of the WIPP Disposal System: Controlled Area and Repository/Shaft System. The repository/shaft system scale is exaggerated. The proposed land-withdrawal boundary is shown at the same scale as the maximum extent of the controlled area (Bertram-Howery and Hunter, 1989a).

isolation while allowing the [DOE] adequate flexibility to handle specific uncertainties that may be encountered" (ibid.).

EPA clearly intended qualitative considerations to have equal weight with quantitative analyses in determining compliance with Subpart B. EPA stated that "the numerical standards chosen for Subpart B, by themselves, do not provide either an adequate context for environmental protection or a sufficient basis to foster public confidence..." (U.S. EPA, 1985, p. 38079). EPA also stated that "factors such as [food chains, ways of life, and the size and geographical distributions of populations] cannot be usefully predicted over [10,000 years]....The results of these analyses should not be considered a reliable projection of the 'real' or absolute number of health effects resulting from compliance with the disposal standards" (U.S. EPA, 1985, p. 38082).

The EPA's assumptions regarding performance assessments and uncertainties are incorporated in Appendix B of the Standard, which the EPA intends the implementing agencies to follow. The EPA intended these assumptions to "discourage overly restrictive or inappropriate implementation" of the requirements (U.S. EPA, 1985, p. 38077). The guidance in Appendix B to the Standard indicates that "compliance should be based upon the projections that the [DOE] believes are more realistic....Furthermore,...the quantitative calculations needed may have to be supplemented by reasonable qualitative judgments in order to appropriately determine compliance with the disposal standards" (U.S. EPA, 1985, p. 38076). In particular, Appendix B states:

> 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.

The qualitative section of the Containment Requirements (§ 191.13(b)) states that:

> 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 the record before the [DOE], that compliance with 191.13(a) will be achieved.

The EPA stated in the supplementary information published with the Standard that the agency recognized that too many uncertainties exist in projecting the behavior of natural and engineered components for 10,000 years and there are too many opportunities for errors in calculations or judgments for the numerical requirements to be the sole basis for determining the acceptability of a disposal system. Qualitative Assurance Requirements were included in the Standard to ensure that "cautious steps are taken to reduce the problems caused by these uncertainties". These qualitative Assurance Requirements are "an essential complement to the quantitative Containment Requirements" (U.S. EPA, 1985, p. 38079). Each qualitative requirement was chosen to compensate for some aspect of the inherent uncertainty in projecting the future performance of a disposal system. The Assurance Requirements begin by declaring that compliance with their provisions will "provide the confidence needed for long-term compliance with the requirements of 191.13."

Determining compliance with Subpart B depends on the estimated overall probability distribution of cumulative releases and on the estimated annual doses; however, it also depends on the strength of the assurance strategies (U.S. DOE, 1987a) that will be implemented and on the qualitative judgment of the DOE and its analysts. The preceding discussion clearly demonstrates the EPA's recognition of the difficulties involved in predicting the future and in quantifying the outcomes of future events. The EPA clearly expects the DOE to understand the uncertainties in the disposal system's behavior to the extent practical, while recognizing that substantial uncertainties will nevertheless remain.

The Standard (as promulgated in 1985) is reproduced in Appendix A of this report.

STATUS OF THE STANDARD

Subpart B of the Standard was vacated and remanded to the EPA by the United States Court of Appeals for the First Circuit in July 1987. The Court found that the EPA had neither reconciled the Individual Protection Requirements with Part C of the Safe Drinking Water Act nor explained the divergence between the two sets of criteria; furthermore, the EPA had not explained the basis for the 1,000-year design criterion in the Individual Protection Requirements. The Court also found that the Groundwater Protection Requirements were promulgated without proper notice and comment. The Second Modification to the Consultation and Cooperation Agreement (U.S. DOE and State of New Mexico, 1981) commits the WIPP Project to proceed with the evaluation of compliance with the Standard as first promulgated until such time as a revised Standard becomes available. Therefore, this report discusses the Standard as first promulgated. Compliance plans for the WIPP will be revised as necessary in response to any changes in the Standard resulting from the court's decision.

Description of the WIPP Project

This section presents the mission of the WIPP Project and identifies the participants in the Project, then briefly describes the physical setting, the repository/shaft system, and the waste.

MISSION

Congress authorized the WIPP in 1979 (Public Law 96-164, 1979) as a research and development facility. The WIPP is designed as a full-scale pilot plant to demonstrate the safe management, storage, and disposal of TRU defense waste. The WIPP performance assessment will help the DOE determine whether the WIPP will isolate wastes from the accessible environment sufficiently well to satisfy the disposal requirements in Subpart B of the Standard. Predictions with respect to compliance with Subpart B of the Standard will provide input to the decision on whether WIPP will become a disposal facility. That decision is expected upon completion of the performance assessment. The DOE will apply Subpart A of the Standard to the WIPP beginning with the first receipt of TRU waste (U.S. DOE, 1989a). "Disposal," as defined in the Standard, will occur when the mined repository is sealed and decommissioned.

PARTICIPANTS

The DOE is the implementing agency, as defined in the Standard, for the WIPP Project. The WIPP Project is managed by the DOE Albuquerque Operations Office (DOE/AL) through the DOE WIPP Project Office (DOE/WPO) in Carlsbad, New Mexico. The WPO is assisted by two prime contractors: Westinghouse Electric Corporation (WEC) and Sandia National Laboratories (SNL). The operating contractor will be responsible for operations after the decision to permanently emplace waste at the WIPP and is also responsible for compliance with Subpart A and with the Assurance Requirements of Subpart B of the Standard. WEC is the management and operating contractor during the test phase. SNL, as scientific advisor, investigates salt-bed disposal of TRU waste, characterizes the site, performs analyses, designs engineered barriers, conducts in situ tests, and evaluates compliance with the long-term performance criteria in Subpart B of the Standard.

The DOE and the State of New Mexico have had an Agreement for Consultation and Cooperation since 1981 (U.S. DOE and State of New Mexico, 1981). This agreement ensures that the State, through the Environmental Improvement Division (EID) and the Environmental Evaluation Group (EEG), has an active part in assuring that public safety issues are fully addressed. In addition, review of the WIPP Project is provided by the National Research Council's Board of Radioactive Waste Management (BRWM) WIPP Panel, the Advisory Committee on Nuclear Facility Safety, the DOE Blue Ribbon Panel, and the Defense Nuclear Facilities Safety Board. Informal review of the compliance evaluation is provided by the EPA. The WIPP also receives close public scrutiny.

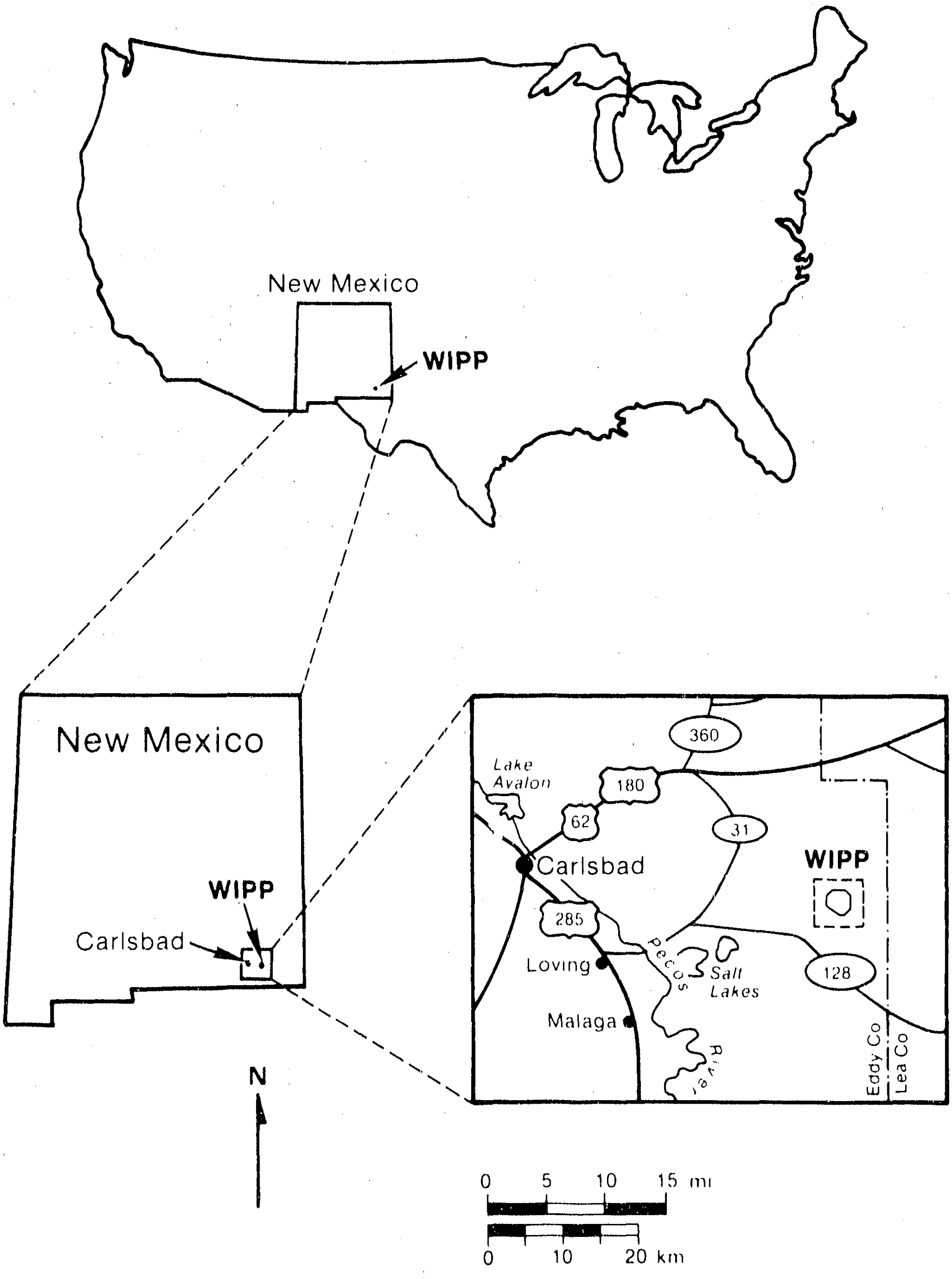
PHYSICAL SETTING

The characteristics of the WIPP are described in detail in the WIPP *Final Safety Analysis Report* (FSAR) (U.S. DOE, 1990b). The WIPP (Figure I-4) is in southeastern New Mexico, about 42 km (26 mi) east of Carlsbad, the nearest population center (pop. 27,000). The area surrounding the WIPP has a low population density. Two smaller communities, Loving (pop. 1,500) and Malaga (pop. 150), are about 33 km (20 mi) to the southwest. Less than 30 permanent residents live within a 16-km (10-mi) radius. The nearest residents live in a ranch house about 5.6 km (3.5 mi) south of the WIPP surface facility (U.S. DOE, 1990b).

The surface of the land proposed for withdrawal has been leased for cattle grazing. At present, none of the ranches within ten miles use well water for human consumption because the quality of the water is too poor. Water for people and most livestock is supplied by pipeline (U.S. DOE, 1990b).

Potash, oil, and gas are the only known important mineral resources; however, resource extraction is not allowed within the proposed land withdrawal boundaries. The volumes and locations of these resources are estimated in the *Final Environmental Impact Statement* (FEIS) for the WIPP (U.S. DOE, 1980a). The surrounding area is used primarily for grazing, potash mining, and oil and gas exploration. About 56 oil and gas wells are within a radius of 16 km (10 mi); the wells generally tap Pennsylvanian strata, about 4,200 m (14,000 ft) deep. The nearest well is about 3 km (2 mi) to the south-southwest of the waste panels. Three potash mines and two associated chemical processing plants are between 8 and 16 km (5 and 10 mi) away. Potash mining is anticipated within a radius of 3 to 8 km (2 to 5 mi) (U.S. DOE, 1990b). The potash zone is about 137 m (450 ft) thick and is encountered about 457 m (1,500 ft) below the surface (Figure I-5).

The WIPP is in the Delaware Basin between the high plains of West Texas and the Guadalupe and Sacramento Mountains of southeastern New Mexico. In the area are four prominent surface features—Los Medaños ("The Dunes"), Nash Draw, Laguna Grande de la Sal, and the Pecos River (Figures I-6 and I-7).



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3 Figure I-4. WIPP Location Map (after Bertram-Howery and Hunter, 1989b).

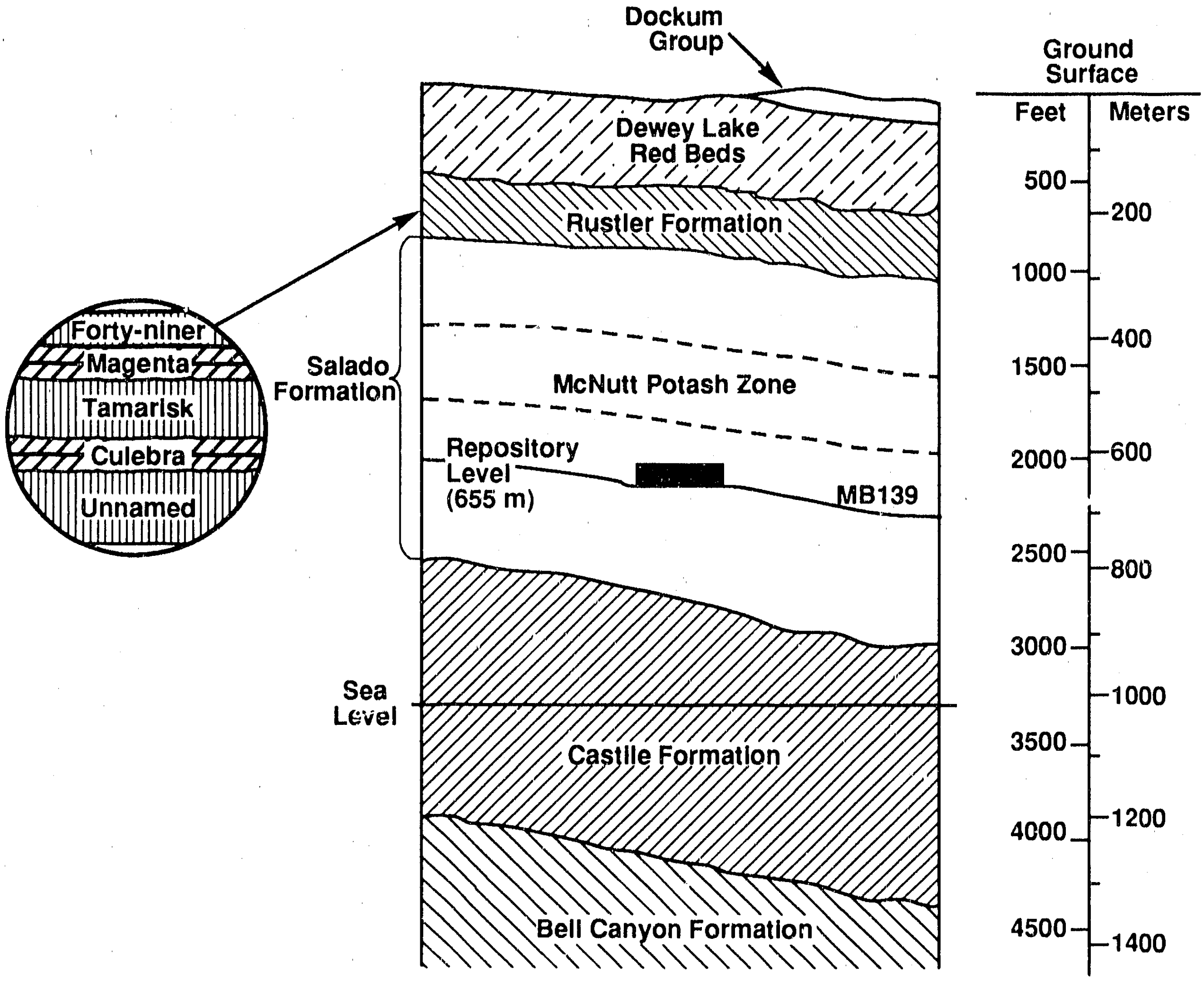

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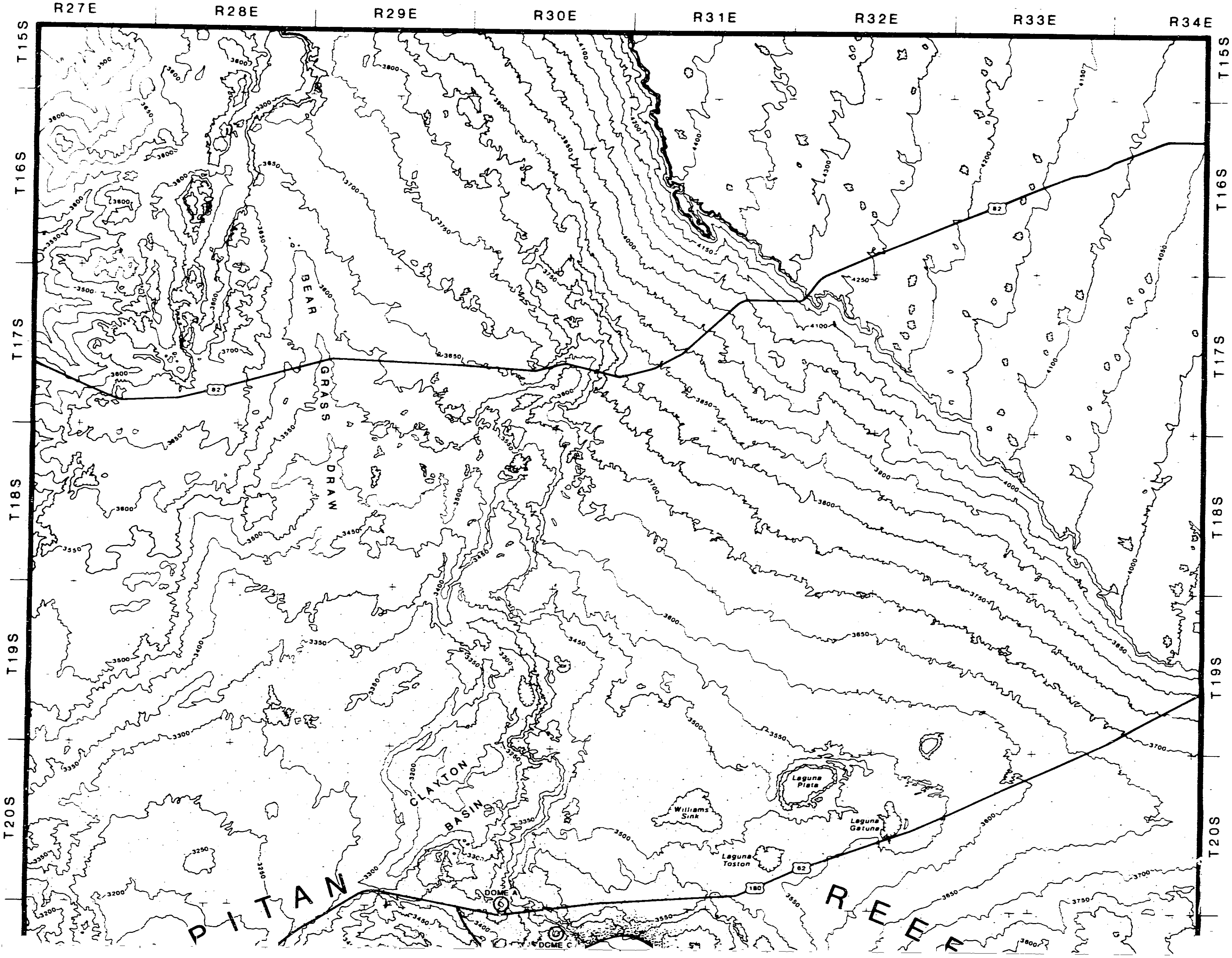
Figure I-5. WIPP Stratigraphy (modified from Rechard, et al., 1990a).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82
180
BEAR
GRASS
DRAW
CLAYTON
BASIN
Laguna Plata
Laguna Gatuna
Laguna Toston
Williams Sink
DOME A
DOME C
PITAN
REEF

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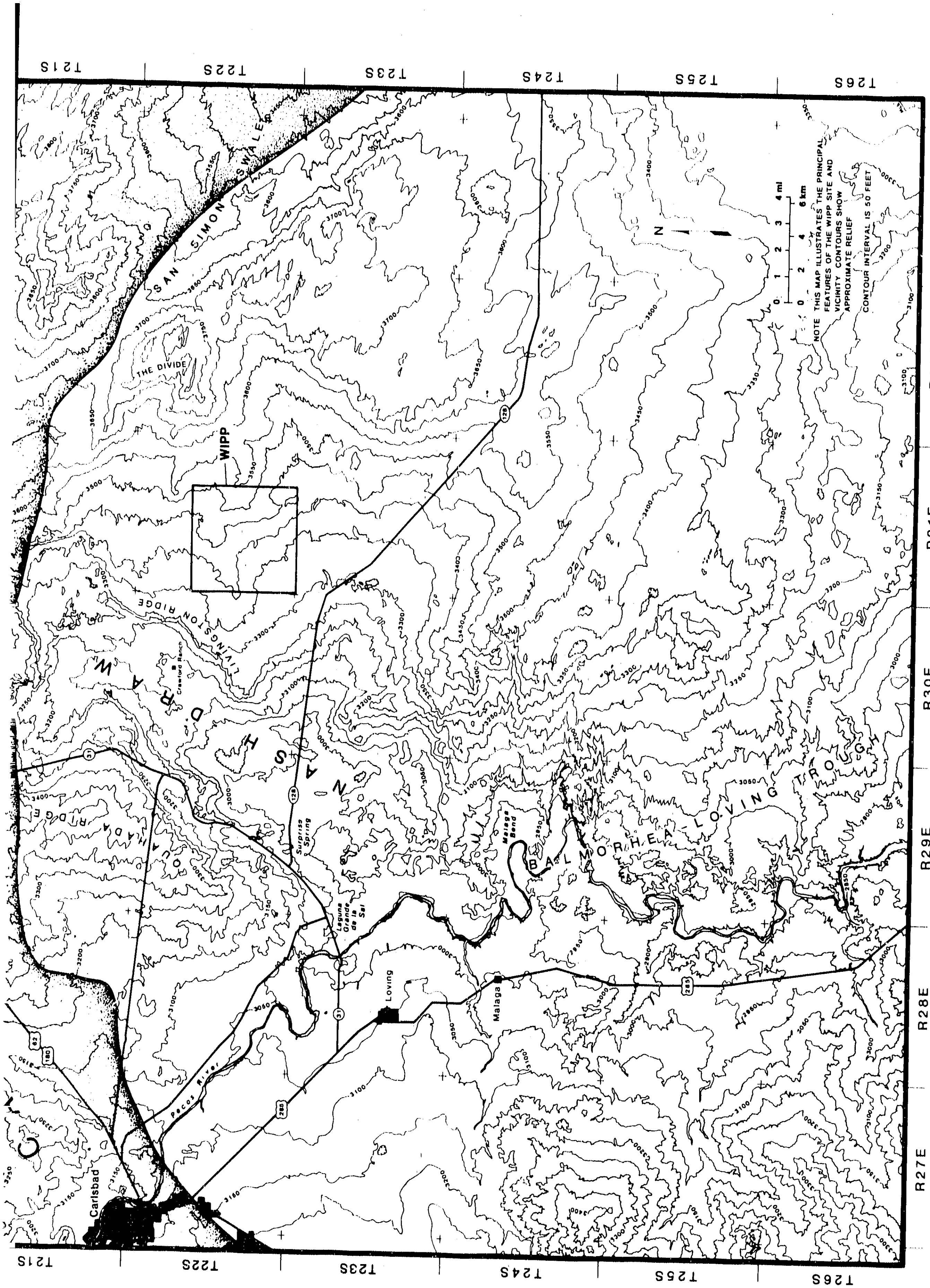

Figure I-6. Topographic Map of the WIPP Area.

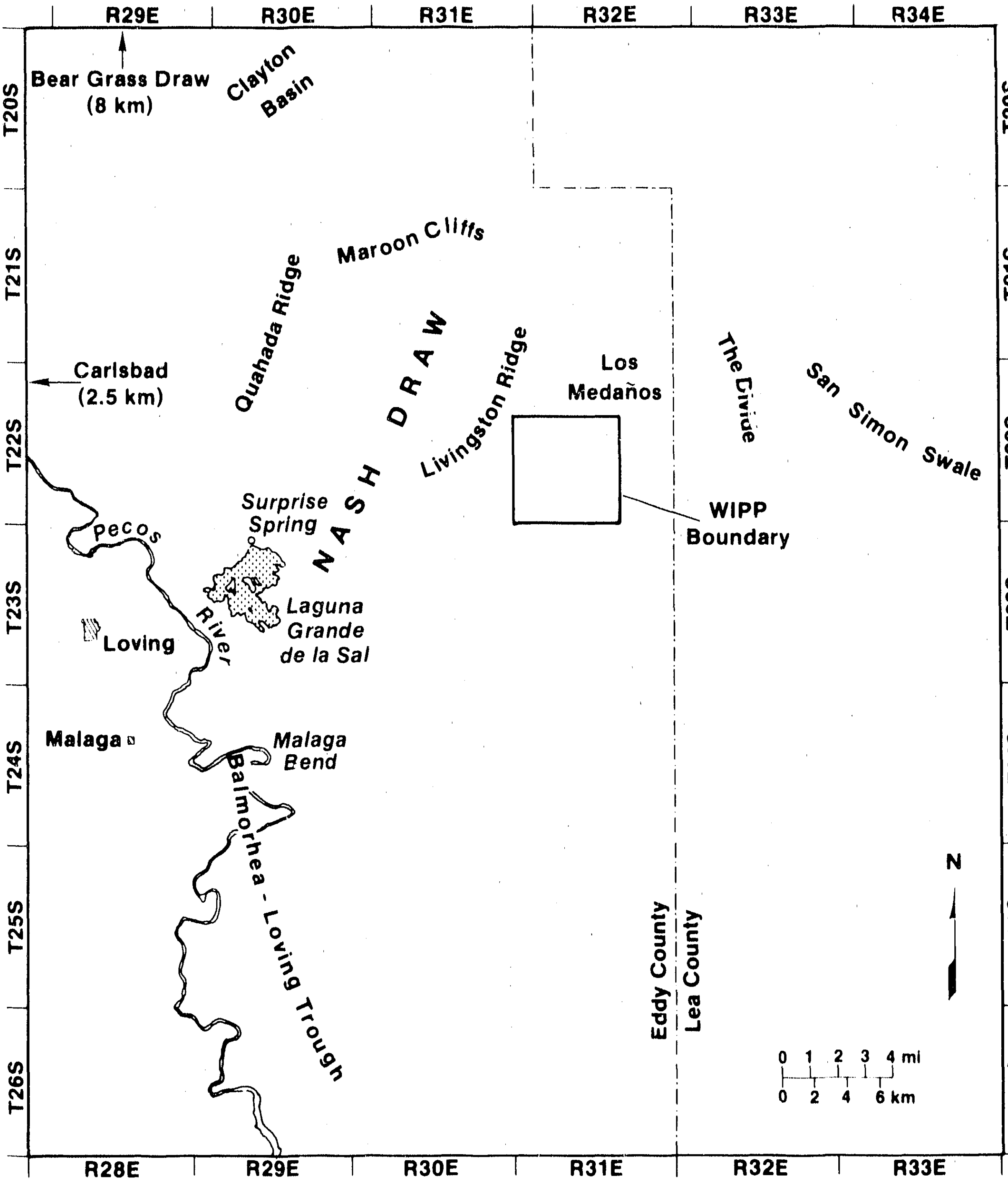

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Figure I-7. Map of the WIPP Area, Showing Physiographic Features.

Los Medaños is a region of gently rolling hills that slopes upward to the northeast from Livingston Ridge on the eastern boundary of Nash Draw to a low ridge called "The Divide." The WIPP is in Los Medaños.

Nash Draw, 8 km (5 mi) west of the WIPP, is a broad, shallow topographic depression with no external surface drainage. Nash Draw extends northeast about 35 km (22 mi) from the Pecos River east of Loving, New Mexico, to the Maroon Cliffs area. This feature is bounded on the east by Livingston Ridge and on the west by Quahada Ridge.

Laguna Grande de la Sal, about 9.5 km (6 mi) west-southwest of the WIPP, is a large playa about 3.2 km (2 mi) wide and 4.8 km (3 mi) long formed by coalesced collapse sinks that were created by dissolution of evaporite deposits. In the geologic past, a relatively permanent, saline lake occupied the playa. In recent history, however, the lake has undergone numerous cycles of filling and evaporation in response to wet and arid seasons, and effluent from the potash and oil and gas industries has enlarged the lake. The lake contains fine sand, clay, and evaporite deposits (Bachman, 1974).

The Pecos River, the principal surface-water feature in southeastern New Mexico, flows southeastward, draining into the Rio Grande in western Texas. At its closest point, the river is about 20 km (12 mi) southwest of the WIPP. Surface drainage from the WIPP does not reach the river or its ephemeral tributaries.

Geologic History of the Delaware Basin

The Delaware Basin, an elongated, confined depression, extends from just north of Carlsbad, New Mexico, into Texas west of Fort Stockton (Figure I-8). The basin covers over 33,000 km^2 (12,750 mi^2) and is filled to depths as great as 7,300 m (24,000 ft) with sedimentary rocks (Hills, 1984).

Geologic history of the Delaware Basin (Powers et al., 1978; Cheeseman, 1978; Williamson, 1978; Hiss, 1975; Hills, 1984; Harms and Williamson, 1988; Ward et al., 1986) began about 450 to 500 million years ago when a broad, low depression formed during the Ordovician Period as transgressing seas deposited clastic and carbonate sediments. After a long period of accumulation and subsidence, the depression separated into the Delaware and Midland Basins when the area now called the Central Basin Platform uplifted during the Pennsylvanian Period, about 300 million years ago.

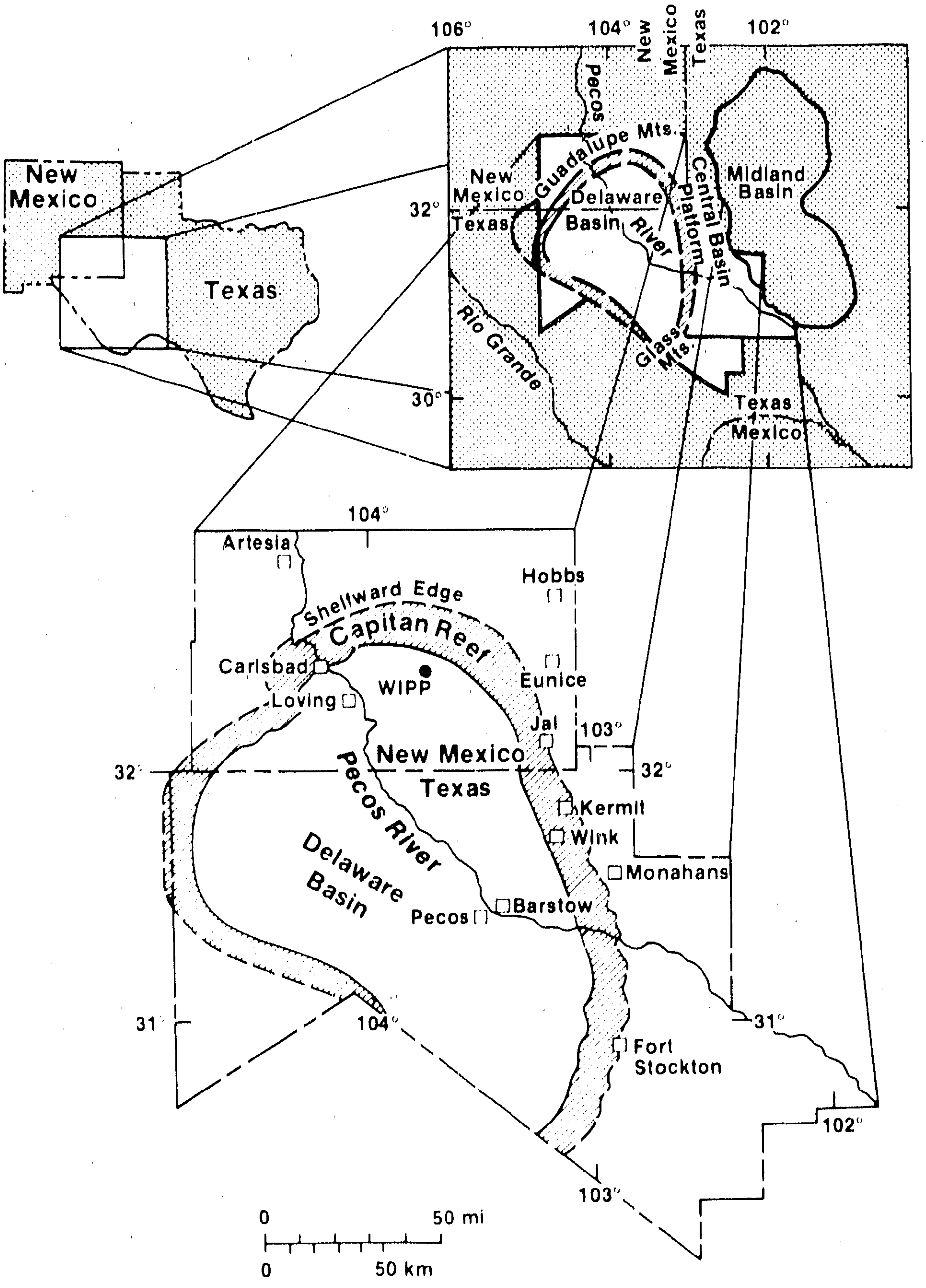
Rock units representing the Permian Period through the Quaternary Period are shown in Table I-1. During the early and middle Permian Period, the Delaware Basin subsided more rapidly, resulting in a sequence of clastic rocks rimmed by reef limestone. The thickest of the reef deposits, the Capitan Limestone,

TABLE I-1. MAJOR STRATIGRAPHIC AND TIME DIVISIONS, SOUTHEASTERN NEW MEXICO

Era	System	Series	Formation	Age Estimate
Cenozoic	Quaternary	Holocene	Windblown sand	
		Pleistocene	Mescalero Caliche	~500,000 yr
			Gatuña Formation	~600,000 ± yr
	Tertiary	Pliocene Miocene	Ogallala Formation	5 million yr
				25 million yr
		Oligocene Eocene Paleocene	Absent Southeastern New Mexico	
				65 million yr
Mesozoic	Cretaceous	Upper (Late)	Absent Southeastern New Mexico	
		Lower (Early)	Detritus preserved	
				144 million yr
	Jurassic		Absent Southeastern New Mexico	
				208 million yr
	Triassic	Upper (Late)	Dockum Group	
		Lower	Absent Southeastern New Mexico	
				245 million yr
Paleozoic	Permian Late	Ochoan	Dewey Lake Red Beds Rustler Formation Salado Formation Castile Formation	
	Middle	Guadalupian	Capitan Limestone and Bell Canyon Formation	
	Early	Leonardian Wolfcampian	Bone Springs Wolfcamp	
				275 million yr

Source: Modified from Bachman, 1987

is buried north and east of the WIPP but is exposed at the surface in the Guadalupe Mountains to the west (Figure I-8). Evaporite deposits of the Castile Formation and the Salado Formation, which hosts the WIPP, filled the basin during the late Permian Period and extended over the reef margins. Evaporites, carbonates, and clastic rocks of the Rustler Formation and the Dewey Lake Red Beds were deposited above the Salado Formation before the end of the Permian Period.



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2 Figure I-8. Location of the WIPP in the Delaware Basin (modified from Richey et al., 1985).

Beginning with the Triassic Period and continuing to the present, the geologic record for the area is marked by long periods of non-deposition and erosion. Those formations that are present are either relatively thin or discontinuous and are not included in the performance assessment of the WIPP. The older, Permian-Period deposits below the Dewey Lake Red Beds were not affected by erosional processes during the past 250 million years. Site characterization activities for the WIPP have determined that no water has flowed through the Salado Formation since it was deposited (Lappin, 1988).

Minimal tectonic activity has occurred in the region since the Permian Period (Hayes, 1964; Williamson, 1978; Hills, 1984). Faulting during the late Tertiary Period formed the Guadalupe and Delaware Mountains along the western edge of the basin. The most recent igneous activity in the area was during the mid-Tertiary Period about 35 million years ago and is evidenced by a lamprophyre dike of fine-grained porphyritic material 16 km (10 mi) northwest of the WIPP (Powers et al., 1978). Major volcanic activity last occurred over 1 billion years ago during Precambrian time (Powers et al., 1978). None of these processes affected the Salado Formation in the vicinity of the WIPP.

Stratigraphy and Geohydrology

The Bell Canyon Formation of the Delaware Mountain Group is the deepest hydrostratigraphic unit currently being considered in the performance assessment (Figure I-5). Understanding fluid flow in the Bell Canyon is necessary because oil and gas drilling into deeper Pennsylvanian strata could penetrate the WIPP and the saturated channel sands of the Bell Canyon Formation.

The Castile Formation consists of seven lithologic members that in the vicinity of the WIPP include three anhydrite members intercalated with two halite members. The Castile Formation is of interest because it contains pressurized brine that could affect repository performance if penetrated by an exploratory borehole. Hydrologic and geochemical data indicate that the brine occurs as hydraulically isolated, stagnant pockets of fluid (Lambert, 1978; Lappin, 1988). These occurrences have been referred to as pressurized brine "pockets" or "reservoirs" in the WIPP literature. The origin of the fluids within the Castile Formation probably includes interstitial entrapment of connate water subsequent to deposition, conversion by dehydration of the original gypsum to anhydrite (Popielak et al., 1983), and movement by meteoric waters from the Capitan into the fractured anhydrites (Lappin, 1988). In the WIPP area, the Castile Formation has no regional flow system.

The Salado Formation is about 600 m (2,000 ft) thick and consists of three informal members:

> A lower member, mostly halite with lesser amounts of anhydrite, polyhalite, and glauberite, with some layers of fine clastic material. The unit is 296 to 354 m (960 ft to 1160 ft) thick, and the WIPP repository is located within it, 655 m (2,150 ft) below the land surface (Jones, 1978). Marker Bed 139 (MB139), an anhydritic bed about 1 m in thickness that is a potential pathway for radionuclide transport to the repository shafts, also occurs in this unit, about 1 m or less below the repository (Lappin, 1988).
>
> A middle member, the McNutt Potash Zone, a reddish-orange and brown halite with deposits of sylvite and langbeinite from which potassium salts are mined (Jones, 1978).
>
> An upper member, a reddish-orange to brown halite interbedded with polyhalite, anhydrite, and sandstone (Jones, 1978).

In the WIPP vicinity, where the Salado Formation is intact, groundwater circulation is minimal or non-existent because primary porosity and open fractures are lacking in the highly plastic salt (Mercer, 1983). The formation may be saturated, but low effective porosity allows for very little groundwater movement.

The Rustler-Salado contact residuum, a zone of dissolution residue, occurs above the halite of the Salado Formation. The residuum recharges east of the WIPP and discharges south-southwest at the river (Brinster, in prep.). Recharge and discharge is not fully understood, although connection to Laguna Grande de la Sal has been investigated (Robinson and Lang, 1938; Mercer, 1983). The water in the Rustler-Salado contact residuum is brine that becomes more concentrated as it moves toward the southwest and becomes nearly saturated in the lower region of Nash Draw near the Pecos River.

The Rustler Formation, the youngest unit of the Late Permian evaporite sequence, includes hydrostratigraphic units that provide potential pathways for radionuclide migration away from the WIPP. Five units of the Rustler, in ascending order, have been described (Vine, 1963; Mercer, 1983):

> The unnamed lower member, composed mostly of fine-grained, silty sandstones and siltstones interbedded with anhydrite west of the WIPP but with increasing amounts of halite to the east.
>
> The Culebra Dolomite Member, a microcrystalline, grayish dolomite or dolomitic limestone with solution cavities containing some gypsum and anhydrite filling.
>
> The Tamarisk Member, composed of anhydrite interbedded with thin layers of claystone and siltstone, with some halite just east of the WIPP.
>
> The Magenta Dolomite Member, a very-fine-grained, greenish-gray dolomite with reddish-purple layers.

The Forty-niner Member, consisting of anhydrite interbedded with a layer of siltstone, with halite present east of the WIPP.

Groundwater flow in the Rustler Formation is restricted mostly to the Culebra Dolomite and Magenta Dolomite Members. The intervening units (the unnamed lower member, the Tamarisk Member, and the Forty-niner Member) are considered aquitards because of their low permeability throughout the area.

Groundwater flow in the Culebra Dolomite Member west of the WIPP is northeast to southwest, and the flow is roughly parallel to the axis of Nash Draw (Brinster, in prep.). Northeast and east of the WIPP, data are insufficient to be conclusive. South of the WIPP, flow is inferred to be southward. Recharge is apparently from the north, possibly at Bear Grass Draw where the Rustler Formation is near the surface and at Clayton Basin where karst activity has disrupted the Culebra Dolomite (Mercer, 1983; Brinster, in prep.). Recharge from units above or below the Culebra Dolomite requires water to pass through what is assumed to be material of very low permeability but could be accomplished via dissolution fractures or large collapse features. Discharge is to the west-southwest either into the Pecos River at Malaga Bend, into the Balmorhea-Loving Trough, or into both. Culebra Dolomite Member water contains large amounts of total dissolved solids.

The Magenta Dolomite Member produces small amounts of water from a thin, silty dolomite, along bedding planes of rock units, and along fractures (Mercer, 1983). The unit is present locally at the WIPP but is absent because of erosion in the southern part of Nash Draw. Recharge to the Magenta Dolomite probably occurs to the north, possibly in Clayton Basin, or farther north at Bear Grass Draw where the Rustler Formation crops out (Mercer, 1983). Discharge is probably into the lower units. Flow direction is similar to Culebra Dolomite Member flow and is either toward Malaga Bend or more directly southward to the Balmorhea-Loving Trough.

Rock units younger than the Rustler Formation are not hydrologically important because they are not extensive and are unsaturated throughout most of the WIPP area. However, the units are discussed here because saturation could occur as a result of climatic changes or a breach of a pressurized brine reservoir. Overlying the Rustler Formation are the youngest Permian rocks, the Dewey Lake Red Beds. The Dewey Lake Red Beds consist of alternating layers of reddish-brown, fine-grained sandstones and siltstones cemented with calcite and gypsum (Vine, 1963). Drilling has identified only a few localized zones of relatively high permeability (Mercer, 1983; Beauheim, 1987). Only three wells in the WIPP area produce small amounts of water from the Dewey Lake Red Beds for livestock (Cooper and Glanzman, 1971).

Water percolating downward through fractures to bedding planes and fine-grained lenticular sandstones recharges the Dewey Lake Red Beds locally, and the water then discharges to lower zones (Mercer, 1983). The Dewey Lake Red Beds form a relatively contiguous surface unit above the WIPP repository.

The Dewey Lake Red Beds are unconformably overlain east of the WIPP by Triassic rocks of the undifferentiated Dockum Group (Figure I-7). The lower Dockum is composed of poorly sorted, angular, coarse-grained to conglomeratic, thickly bedded material interfingering with shales. The undifferentiated Dockum Group is the chief source of water for domestic and livestock use in eastern Eddy County away from the WIPP and in western Lea County (Nicholson and Clebach, 1961; Richey et al., 1985). Recharge to the Triassic rocks is mainly from precipitation on overlying alluvium and sand dunes.

A long depositional hiatus occurred from Triassic time to the late Tertiary Period (Table I-1). No rocks represent the Jurassic or Cretaceous Periods east of the Pecos River. The Tertiary Period is represented by a very thin Ogallala Formation remnant present only at The Divide west of San Simon Swale. The Quaternary Period is represented by the Gatuña Formation, which occurs as a discontinuous flood-plain deposit in channels and depressions (Bachman, 1980, 1984; Mercer, 1983); the informally named Mescalero caliche; and localized accumulations of alluvium and dune sands.

REPOSITORY/SHAFT SYSTEM

The WIPP repository is in the 250-million-year-old Salado Formation. Groundwater movement in the Salado is extremely limited; the repository will remain dry while ventilated, but slow seepage of interstitial brine does occur.

If the DOE successfully demonstrates compliance with the Standard, the WIPP is expected to become the nation's first and only large-scale, mined geologic repository for TRU waste (Figure I-9). Ultimately, eight panels of seven rooms each will be mined. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be backfilled and sealed, waste will be placed in the drifts between the panels and backfilled, and access ways will be sealed off from the shafts. Because the WIPP is a research and development facility, an extensive experimental area is also in use and under construction north of the waste-disposal area (Bertram-Howery and Hunter, 1989b).

The WIPP underground workings are composed of four shafts connected to a single underground disposal level. All shafts have four principal components: a collar; a lined section penetrating the rock overburden; an unlined section penetrating the salt; and a key at the rock/salt contact

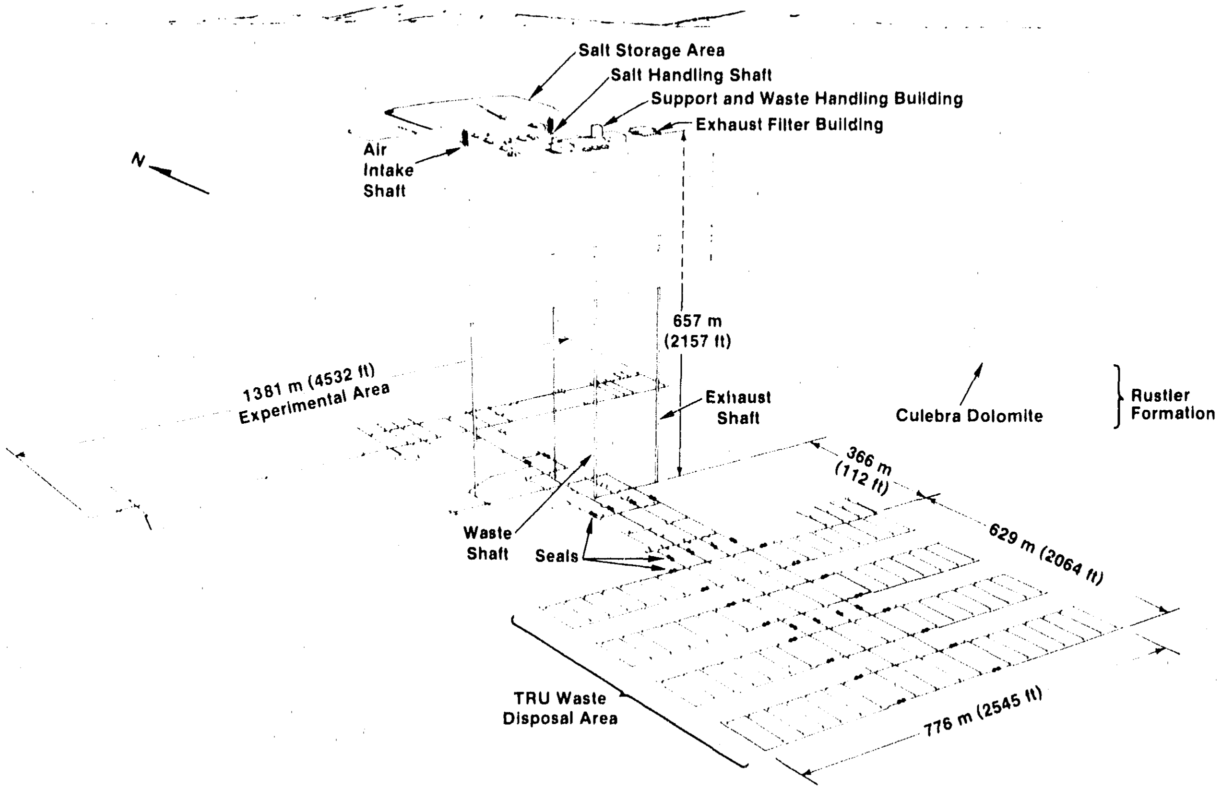

Figure I-9. Proposed WIPP Repository, Showing Both TRU-Waste Disposal Areas and Experimental Areas (after Waste Management Technology Dept., 1987).

about 260 m (850 ft) below the surface to provide a transition from the lined section to the unlined section. The lined portion of the exhaust shaft is 4 m (14 ft) in diameter. The salt handling shaft provides the only means for removing mined materials and serves as the secondary air supply. This shaft also provides access for personnel. The lined section is 3 m (10 ft) in diameter. The air intake shaft serves as the primary air intake opening; the lined portion is 5 m (16 ft) in diameter. This shaft provides backup egress for personnel and material. The waste shaft is designed to permit the transport of radioactive waste between the surface waste-handling facilities and the underground disposal area; the lined portion is 6 m (19 ft) in diameter. This shaft also provides access for personnel, materials, large equipment, and diesel fuel. The shafts will be sealed upon decommissioning of the WIPP (U.S. DOE, 1990b).

Access and disposal openings are designed to remain stable and provide minimum clearance for equipment during waste emplacement; salt creep will eventually close these openings. The 100-acre underground disposal area accommodates waste handling, waste disposal, operations, and maintenance. All underground horizontal openings are rectangular in cross section. The disposal area drifts, in the southern part of the repository, are 4 m (13 ft) high by 8 m (25 ft) wide; the disposal rooms are 4 m (13 ft) high, 10 m (33 ft) wide, and 91 m (300 ft) long. Other drifts range from about 2 to 4 m (8 to 12 ft) high and 4 to 8 m (14 to 25 ft) wide. The width of the pillars between rooms is 30 m (100 ft). The drift entries to the disposal areas will be sealed to isolate the disposal panels. The conceptual design envisions a multiple-component seal approximately 30 m (100 ft) long (U.S. DOE, 1990b).

WASTE

The TRU waste for which WIPP is designed is defense-program waste generated by United States government activities. TRU wastes are those radioactive wastes that, without regard to source or form, are contaminated with concentrations greater than 100 nCi/g of alpha-emitting, transuranic radionuclides with half-lives greater than 20 years. In accordance with DOE Order 5820.2A (U.S. DOE, 1980b), heads of DOE Field Organizations can determine that other alpha-contaminated wastes, peculiar to a specific waste-generator site, must be managed as TRU wastes. The WIPP *Waste Acceptance Criteria* (WAC) (Westinghouse, 1989) determine which TRU wastes will be accepted for emplacement at the WIPP. Under current plans, most TRU waste generated since 1970 will be disposed of at the WIPP; a small amount will be disposed of at other DOE facilities.

Waste Form

Most of the waste can be contact handled (CH) because the external dose rate (200 mrem/h or less) permits people to handle properly sealed drums and boxes without any special shielding. CH-TRU waste to be shipped to the WIPP is contained in 55-gallon drums, metal boxes, and fiberglass-reinforced plywood (FRP) boxes (Table I-2). Because the WIPP *Waste Acceptance Criteria* requires a metal overpack for all combustible boxes as a fire prevention measure, FRP boxes and any other non-metal boxes will be overpacked and subsequently handled and disposed of in these overpacks. CH-TRU waste in drums and boxes will be stacked three high in the waste-storage rooms.

A small portion of the waste volume must be remotely handled (RH); that is, the surface dose rate exceeds 200 mrem/h so that the waste canisters must be packaged for handling and transportation in specially shielded casks. The surface dose rate of RH-TRU canisters cannot exceed 1,000 rem/h; however, no more than 5 percent of the canisters can exceed 100 rem/h. RH-TRU waste in canisters will be emplaced in holes drilled into the walls of the rooms. The reference canister for the RH-TRU waste is a 26-in O.D. (outside diameter) right-circular cylinder made of 1/4-in carbon steel plate. Caps are welded at both ends. The canister is 3 m (10 ft) in length, including the handling pintle. Inside, the waste occupies about 850 ℓ (30 ft^3) (U.S. DOE, 1990b).

The WIPP's capacity is equivalent to about 863,000 drums containing about 10,000,000 Ci of CH-TRU waste and no more than 5,100,000 Ci of RH-TRU waste. The total curies of RH-TRU waste is limited by the First Modification to the Consultation and Cooperation Agreement (U.S. DOE and State of New Mexico, 1981). The complex analyses for evaluating compliance with Subpart B of the Standard require knowledge of the waste inventory. Therefore, all analyses will be based on current projections of the final inventory, estimated at 385,000 drums and 19,500 boxes of CH-TRU waste (Lappin et al., 1989, Appendix A.9) and 4,000 to 5,000 canisters of RH-TRU waste (U.S. DOE, 1990b). The wastes are classified as retrievably stored or newly generated. Ten defense facilities eventually will ship TRU waste directly to the WIPP (Table I-3).

Typically, the waste is composed of laboratory and production trash contaminated with transuranic elements. This includes cloth, rubber, polyethylene, paper, wood, metals, glass, filters, resins, graphite, oils, solvents, alcohols, and sludges. The sludges may contain a solidifier (such as cement), absorbent materials, inorganic compounds, complexing agents, and organic compounds including oils, solvents, alcohols, emulsifiers, surfactants, and detergents. For acceptance at the WIPP, the waste must be stabilized or packaged so that it cannot propagate fires. Only small amounts of free liquids are allowed in the packages. The density of CH-TRU waste is

TABLE I-2. APPROVED CH-TRU WASTE CONTAINERS FOR TRANSPORTATION AND EMPLACEMENT AT THE WIPP FACILITY

Container Description	Container Dimension (h x w x l)	Nominal Volume
DOT 17C 55 Gallon Steel Drums	0.9 x 0.1 m dia (35 x 24 in)	0.2 m^3 (7.4 ft^3)
Steel Box	1.0 x 1.4 x 1.7 m (38 x 54 x 68 in)	2.3 m^3 (82 ft^3)
Steel Box	2.0 x 1.7 x 2.8 m (77 x 68 x 112 in)	9.5 m^3 (339 ft^3)
Steel Box (FRP Box Overpacked)	1.4 x 1.4 x 2.2 m (54 x 54 x 88 in)	4.1 m^3 (148 ft^3)
Seven-Pack of 55-Gallon Steel Drums		1.5 m^3 (52* ft^3)
Standard Waste Box	1.0 x 1.8 x 1.4 m (38 x 71 x 55 in)	1.8 m^3 (64 ft^3)

*Envelope Volume - 2.2 m^3 (78 ft^3)
Source: U.S. DOE, 1990a

assumed to be a maximum of 2.2 g/cm^3 (based on maximum inventory contained in a 55-gallon drum) and is expected to average about 1.0 g/cm^3 (U.S. DOE, 1990b). The following CH-TRU waste forms have been identified as also containing hazardous chemical constituents[1] (U.S. DOE, 1990b). Many of these constituents significantly affect the ability of radionuclides to migrate out of the repository.

Cemented and Uncemented Aqueous Waste. This wastewater treatment sludge is precipitated at a pH of 10 to 12. It is a damp solid that may be cemented. Alcohols and halogenated organics in the sludge are derived from cleaning equipment and glassware and degreasing metals. Some aqueous waste may also contain metals, such as cadmium and lead.

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[1] These hazardous materials are not regulated under 40 CFR Part 191, but are regulated separately by EPA and the State of New Mexico.

Cemented and Uncemented Organic Waste. Organic waste containing oil and halogenated organic solvents is a damp solid that may be cemented and contain an emulsifier. Organic waste consists of lathe coolants and degreasing solvents used in plutonium fabrication.

Solidified Process and Laboratory Solid Waste. This material consists of anion and cation resins and incinerator ash that are neutralized and immobilized with portland cement. Solvents in this waste are from plutonium-recovery operations.

Combustible Waste. This waste includes paper and cloth (dry and damp), various plastics such as polyethylene and polyvinyl chloride, wood, and filters contaminated with trace quantities of halogenated organic solvents. These materials are generated in plutonium-recovery and plutonium-fabrication processes and analytical laboratories.

Metal Waste. Lead, tantalum, stainless steel, and aluminum constitute the majority of these wastes, which include equipment, tools, crucibles, and molds. Residual halogenated organic solvents may also be found in this waste form.

Filter Waste. These wastes are air filters and processed filter media with portland cement added to absorb any residual liquid and neutralize residual acids. Exhaust stream filters may be contaminated with volatile organic solvents used in plutonium fabrication and recovery processes.

Inorganic Solid Waste. Materials such as firebrick, concrete, and soil are included in this waste form, which may be contaminated with residual halogenated organic solvents. This waste results from decontamination and decommissioning of plutonium recovery areas.

Leaded Rubber Waste. This waste includes leaded rubber gloves and aprons used throughout plutonium processing areas.

The estimated quantity of each waste form in CH-TRU waste from two DOE facilities is given in Table I-4. Most of the organic solvents are present in residual quantities from the cleaning of equipment, plastics, glassware, and filters. A major constituent of CH-TRU waste is lead that is present as incidental shielding, glovebox parts, and lead-lined gloves and aprons (U.S. DOE, 1990b). Trace quantities of mercury, barium, chromium, and nickel have also been reported in some sludges (U.S. DOE, 1990b). Two RH-TRU waste forms contain hazardous chemical constituents (U.S. DOE, 1990b):

TABLE I-3. CURRENTLY PROJECTED TOTAL RADIONUCLIDE INVENTORIES BY FACILITY FOR CH- AND RH-TRU WASTE

Waste Facility[b]	Radionuclide inventory (curies)[a]		
	Retrievably Stored[c]	Newly generated[d]	Total
	CH-TRU waste		
Idaho National Engineering Laboratory	3.74×10^5	7.61×10^2	3.75×10^5
Rocky Flats Plant[e]	0	1.05×10^6	1.05×10^6
Hanford Reservation	6.85×10^5	1.10×10^6	1.78×10^6
Savannah River Site	8.59×10^5	3.70×10^6	4.56×10^6
Los Alamos National Laboratory	5.96×10^5	1.61×10^6	2.21×10^6
Oak Ridge National Laboratory	2.80×10^4	3.51×10^4	6.31×10^4
Nevada Test Site[f]	4.73×10^2	0	4.73×10^2
Argonne National Laboratory--East[e]	0	7.13×10^2	7.13×10^2
Lawrence Livermore National Laboratory[e]	0	8.45×10^4	8.45×10^4
Mound Laboratory[e]	0	1.87×10^2	1.87×10^2
Subtotal	2.54×10^6	7.58×10^6	1.01×10^7
	RH-TRU waste		
Idaho National Engineering Laboratory	1.51×10^3	2.28×10^4	2.43×10^4
Hanford Reservation	4.04×10^3	1.93×10^4	2.33×10^4
Los Alamos National Laboratory	3.64×10^3	2.42×10^2	3.88×10^3
Oak Ridge National Laboratory	2.71×10^3	1.84×10^2	2.89×10^3
Argonne National Laboratory--East	0	1.03×10^3	1.03×10^3
Subtotal	1.19×10^4	4.36×10^4	5.54×10^4
TOTAL	2.58×10^6	7.62×10^6	1.02×10^7

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[a] Radionuclide inventories for the waste volumes estimated in the 1987 Integrated Data Base (U.S. DOE, 1987a)--that is, 5.6 million ft^3 of CH-TRU waste and 95,000 ft^3 of RH-TRU waste.

[b] Unless indicated otherwise, these facilities both generate and store TRU waste.

[c] Stored as of December 31, 1986.

[d] Generated between 1987 and 2013.

[e] Facility that generates but does not store TRU waste.

[f] Facility that does not generate TRU waste, but is designated a TRU waste storage facility.

Source: U.S. DOE, 1990c

TABLE I-4. ESTIMATED QUANTITIES OF TRU MIXED WASTE (BY WASTE FORM) FROM ROCKY FLATS PLANT[a,b]

Description of waste form	Quantity (kg)
Cemented and uncemented aqueous waste	1.35×10^7
Cemented and uncemented organic waste	3.27×10^6
Immobilized process and laboratory solids	3.38×10^5
Combustible waste	6.66×10^6
Metal waste	9.65×10^6
Filter waste	2.21×10^6
Inorganic solid waste	4.15×10^5
Leaded rubber waste	3.64×10^5
Total	3.64×10^7

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[a] From the Radioactive Mixed Waste Compliance Manual, (WEC, 1989, Appendix 6.4.1.).

[b] Quantities include waste projected to be generated through the year 2013 and waste in retrievable storage at the Idaho National Engineering Laboratory.

Source: U.S. DOE, 1990b

Solid Waste. This waste contains mixtures of combustibles (e.g., paper, polyvinyl chloride, polypropylene, polyethylene, and neoprene) and noncombustibles (e.g., laboratory equipment, tools, and small electric motors) that were removed from a hot cell facility at Oak Ridge National Laboratory. This waste will not contain free liquids or particulates.

Sludges. Fuel sludges and process sludges will be solidified. This waste will be a solid monolith.

Radionuclide Inventory

The inventory of radionuclides contained in the waste upon receipt at the WIPP has been projected over the 25-year operational lifetime of the repository (Tables I-5 and I-6). The radionuclide composition of CH-TRU

TABLE I-5. REPRESENTATIVE RADIONUCLIDE CONTENT OF CH-TRU WASTE

Radionuclide	Mass g/container		Activity Ci/container
<u>Drum</u>			
Th-232	6.0×10^{0}		6.6×10^{-7}
U-233	1.7×10^{0}		1.7×10^{-2}
U-235	4.0×10^{-1}		8.8×10^{-7}
U-238	1.0×10^{1}		3.5×10^{-6}
Np-237	3.1×10^{-2}		2.2×10^{-5}
Pu-238	6.2×10^{-1}		1.1×10^{1}
Pu-239	1.4×10^{1}		8.5×10^{-1}
Pu-240	8.5×10^{-1}		1.9×10^{-1}
Pu-241	6.6×10^{-2}		6.8×10^{0}
Pu-242	7.8×10^{-3}		3.1×10^{-5}
Am-241	4.9×10^{-1}		1.7×10^{0}
Cm-244	4.2×10^{-4}		3.4×10^{-2}
Cf-252	1.0×10^{-5}		5.4×10^{-3}
		TOTAL	2.1×10^{1}
<u>Standard Waste Box (SWB)</u>			
Th-232	1.2×10^{1}		1.3×10^{-6}
U-233	6.7×10^{0}		6.5×10^{-2}
U-235	9.6×10^{-1}		2.1×10^{-6}
U-238	2.5×10^{1}		8.3×10^{-6}
Np-237	4.4×10^{-4}		3.1×10^{-7}
Pu-238	4.2×10^{-2}		7.2×10^{-1}
Pu-239	7.9×10^{1}		4.9×10^{0}
Pu-240	6.5×10^{0}		1.5×10^{0}
Pu-241	6.7×10^{-1}		6.9×10^{1}
Pu-242	7.5×10^{-2}		2.9×10^{-4}
Am-241	2.1×10^{-1}		7.3×10^{-1}
Cm-244	8.6×10^{-5}		7.0×10^{-3}
Cf-252	2.1×10^{-6}		1.1×10^{-3}
		TOTAL	7.7×10^{1}

Source: U.S. DOE, 1990b

TABLE I-6. REPRESENTATIVE RADIONUCLIDE CONTENT OF RH-TRU WASTE

Radionuclide		Ci/canister	Ci/ℓ
Co-60		1.7×10^{-1}	2.0×10^{-4}
Sr-90		5.1×10^{0}	6.0×10^{-3}
Ru-106		3.5×10^{-2}	4.2×10^{-5}
Sb-125		1.1×10^{-3}	1.2×10^{-6}
Cs-137		4.3×10^{0}	5.0×10^{-3}
Ce-144		3.4×10^{-1}	4.0×10^{-4}
Eu-155		1.7×10^{-3}	2.0×10^{-6}
U-233		5.5×10^{-3}	6.5×10^{-6}
U-235		3.0×10^{-3}	3.6×10^{-6}
U-238		1.5×10^{-3}	1.7×10^{-6}
Pu-238		5.7×10^{0}	6.7×10^{-3}
Pu-239		6.8×10^{0}	8.0×10^{-3}
Pu-240		2.2×10^{0}	2.5×10^{-3}
Pu-241		1.2×10^{1}	1.4×10^{-2}
Pu-242		3.8×10^{-4}	4.5×10^{-7}
Am-241		2.1×10^{-1}	2.5×10^{-4}
Cm-244		1.6×10^{-1}	1.9×10^{-4}
Cf-252		2.8×10^{-1}	3.3×10^{-4}
	TOTAL	3.7×10^{1}	4.3×10^{-2}

Source: U.S. DOE, 1990b

waste varies widely depending upon which DOE facility generated the waste. To simplify radiological analyses, the mean activity of a 55-gallon drum for each generator was weighted based on the estimated number of containers contributed by each facility for disposal in the WIPP. The combined product of this weighted activity with the individual radionuclide distributions in the waste produced by each generator was used to represent the radionuclide content of an average drum shipped to the WIPP (U.S. DOE, 1990b). The existing RH-TRU waste contains a wide range of radionuclides. The average reference RH-TRU waste for the WIPP consists of a normalized actinide inventory and an assumed distribution of mixed activation and fission products. The concentration of all radionuclides in RH-TRU waste will not exceed 23 Ci/ℓ (U.S. DOE, 1990b).

The fissile material content in equivalent grams of plutonium-239 allowed by the WAC is a maximum of 200 g for a 55-gallon drum and 5g/cm^{3} up to 350 g for boxes. The average content is approximately 17 g for a drum and 90 g for the most common box (U.S. DOE, 1990b).

Subpart B of the Standard sets release limits in curies for isotopes of americium, carbon, cesium, iodine, neptunium, plutonium, radium, strontium, technetium, thorium, tin, and uranium, as well as certain other radionuclides (Appendix A of this report). Although the initial WIPP inventory contains little or none of some of the listed nuclides, they may be produced as a result of radioactive decay and must be accounted for in the compliance evaluation; moreover, any radionuclides not listed in Subpart B must be accounted for if those radionuclides could contribute to doses.

Possible Modifications to Waste Form

If ongoing research does not establish sufficient confidence in acceptable performance or indicates a potential for unacceptable performance, modifications to the waste form or backfill could be required. SNL has conducted preliminary research on possible modifications (Butcher, 1990a). The Engineered Alternative Task Force (EATF), assembled by Westinghouse Electric Corporation, will identify specific alternatives, rank alternatives according to specific feasibility criteria, and recommend further research (WEC, 1990; U.S. DOE, 1990d). 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 (Bertram-Howery and Swift, 1990).

II. APPLICATION OF SUBPART B TO THE WIPP

The text of Chapter II is preceded by a synopsis that simplifies concepts presented in Chapter II. Detailed information about those concepts is in the text following the synopsis.

Synopsis

Containment Requirements

The primary objective of the Containment Requirements of the Standard is to isolate the radionuclides from the accessible environment by limiting long-term releases.

Performance Assessment

Subpart B of the Standard specifically defines "performance assessment" as an analysis that:

> Identifies the processes and events that might affect the disposal system.
>
> Examines the effects of these processes and events on the performance of the disposal system.
>
> Estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events.

Performance assessment must provide a reasonable expectation that releases resulting from significant processes and events that may affect the disposal system for 10,000 years after disposal have:

> A likelihood of less than one chance in ten of exceeding quantities specified in Appendix A of the Standard.
>
> A likelihood of less than one chance in 1,000 of exceeding ten times the quantities specified in Appendix A of the Standard.

"Performance assessment" commonly refers to the prediction of all long-term performance; this report refers to the assessment of compliance with both the Containment Requirements and the Individual Protection Requirements as the "WIPP performance assessment."

For the WIPP performance assessment, the disposal system consists of the underground repository, shafts, and man-made barriers and the natural barriers of the disposal site.

The man-made barriers are:

Material placed around the waste containers to fill the open space in the rooms.

Seals in horizontal passageways and entries to the groups of rooms.

Fill material and seals in the shafts.

Plugs in boreholes.

Natural barriers are the subsurface geology and hydrology within the controlled area.

Performance assessments must assume the total absence after 100 yrs of active institutional controls such as post-operational monitoring, maintaining fences and buildings, and guarding the facility.

Probability of Human Intrusion

Performance assessments must consider the probability of human intrusion into the repository within the 9,900-year period after active institutional controls are assumed to end.

Typical examples of human intrusion include but are not limited to exploratory drilling, mining, or construction of other facilities for reasons unrelated to the repository.

The EPA assumes that exploratory drilling for resources is the most severe intrusion that must be considered.

Performance assessments may consider the effectiveness of passive institutional controls such as permanent markers and records to indicate the dangers of the wastes and their location.

Four conclusions have been drawn by the performance-assessment team for the WIPP relative to human intrusion:

> No human intrusion into the repository will occur during the period of active institutional controls. Credit for active institutional controls can be taken only for 100 years after decommissioning.
>
> While passive institutional controls endure, no deliberate resource exploration or exploitation will occur inside the controlled area, but reasonable, site-specific exploitation outside the controlled area may occur and should be considered in the performance assessment.
>
> Inadvertent intrusion into the repository leads to its detection. Intruders will plug and abandon their boreholes to avoid the effects of the repository.
>
> No more than 30 exploratory boreholes/km^2 (0.4 mi^2) will be assumed drilled inside the controlled area in the 10,000 years of regulatory interest. While passive institutional controls endure, the rate for exploratory drilling may be significantly reduced, although the likelihood cannot be eliminated.

Release Limits

Appendix A to the Standard establishes release limits for all regulated radionuclides, based on a calculated "waste unit" that excludes a significant portion of the waste planned to be disposed of at the WIPP. This reduces by over half the allowable releases from the WIPP.

Uncertainties

Performance assessment requires considering numerous uncertainties in the projected performance of the disposal system.

Statistically selected parameter values are used in the WIPP performance assessment for simulating repository performance.

Models will be checked for correctness to the extent possible, but expert judgment must be relied upon where validation is not possible.

Compliance Assessment

Determining the likelihood of intrusion into the repository poses some questions that cannot be answered by numerical modeling or experimentation. All approaches to assessing the probability of intrusion presently being considered must include expert judgment.

The EPA suggests that the results of the performance assessment be assembled into a single complementary cumulative distribution function (CCDF).

A CCDF is a graphical means of showing the probability of exceeding various levels of cumulative release.

According to the EPA, if the CCDF shows that releases have probabilities that do not exceed specified limits, then a disposal system can be considered to be in compliance with the Containment Requirements.

The CCDF could show that some releases have probabilities that exceed the specified limits; compliance must be determined from all information assembled by the DOE, including qualitative judgments.

The likelihood that excess releases will occur must be considered before a qualitative decision can be made about a "reasonable expectation" of compliance.

Modifying the Requirements

The Containment Requirements could be modified by the EPA if:

Complete analyses showed that disposal systems that clearly demonstrated good isolation could not reasonably comply with the requirements.

Additional information indicated that the general requirements were too restrictive or not adequate for certain types of waste.

Assurance Requirements

Each Assurance Requirement applies to some aspect of uncertainty about the future relative to long-term containment by:

Limiting reliance on active institutional controls to 100 years to reduce reliance on future generations to maintain surveillance. Performance-assessment calculations assume these controls will be maintained for 100 years.

Monitoring to mitigate against unexpectedly poor system performance going undetected.

Using markers and records to reduce the chance of systematic or inadvertent intrusion.

Including multiple barriers, both man-made and natural, to reduce the risk should one type of barrier not perform as expected.

Avoiding areas with natural resource potential, unless the favorable characteristics of the area as a disposal site outweigh the possible problems associated with inadvertent human intrusion of the repository.

Designing a system that permits possible future recovery of the wastes for a reasonable period of time after disposal, so that future generations have the option of relocating the wastes should new developments warrant such recovery.

Individual Protection Requirements

The Individual Protection Requirements apply only to undisturbed performance and require predicting potential annual doses to man resulting from releases to the accessible environment during the first 1,000 years after decommissioning of the repository, if performance assessments predict such releases.

The same procedures developed for assessing compliance with the Containment Requirements can be used to predict undisturbed performance of the disposal system.

In predicting the undisturbed performance of the disposal system, reasonable variations from the planned behavior will be considered, based on uncertainties in the numerical values of the design parameters and in the available data.

The EPA assumes that compliance can be determined based upon "best estimate" predictions rather than a CCDF.

One of the requirements is that individuals be assumed to consume 2 ℓ (0.5 gal) per day of drinking water from a significant source of groundwater. The WIPP Project has concluded that:

> No water-bearing unit at the WIPP met the EPA's first definition of significant source of groundwater everywhere prior to construction of the WIPP (or currently). The WIPP Project will assume that any portion of a water-bearing unit that meets the definition is a significant source of groundwater.
>
> No community water system is currently being supplied by any aquifer near the WIPP; therefore, no aquifer meets the second definition of significant source of groundwater.
>
> The nearest aquifer that meets the definition of significant source of groundwater over its entire extent is along the Pecos River. Communication between this aquifer and any other aquifers in the vicinity of the WIPP will be evaluated.

No releases from the undisturbed repository/shaft system are expected to occur within 1,000 years; therefore, dose predictions for undisturbed performance may be unnecessary.

Groundwater Protection Requirements

Special sources of groundwater are protected from contamination at levels greater than certain limits.

> No special sources of groundwater are present at the WIPP; therefore, the requirement to predict concentrations of radionuclides in such groundwater is not relevant.

Subpart B of the Standard applies at the WIPP to probabilities of cumulative releases of radionuclides into the accessible environment (§ 191.13) and to annual radiation doses received by members of the public in the accessible environment (§ 191.15) as a result of TRU waste disposal. Actions and procedures are required (§ 191.14) for increasing confidence that the probabilistic release limits will be met at the WIPP. Radioactive contamination of certain sources of groundwater (§ 191.16) in the vicinity of the WIPP disposal system from such TRU wastes would also be regulated, if any of these sources of groundwater were found to be present (U.S. DOE, 1989a). Each of the four requirements of Subpart B and their evaluation by the WIPP Project is discussed below. The full text of the Standard is reproduced as Appendix A of this report.

Appendix B to the Standard is EPA's guidance to the implementing agency (in this case, the DOE). In the supplementary information published with the Standard in the *Federal Register* (U.S. EPA, 1985, p. 38069), the EPA stated that it intends the guidance to be followed:

> ...Appendix B...describes certain analytical approaches and assumptions through which the [EPA] intends the various long-term numerical standards of Subpart B to be applied. This guidance is particularly important because there are no precedents for the implementation of such long-term environmental standards, which will require consideration of extensive analytical projections of disposal system performance.

The EPA based Appendix B on analytical assumptions it used to develop the technical basis for the numerical disposal standards. Thus, the EPA "believes it is important that the assumptions used by the [DOE] are compatible with those used by the EPA in developing this rule. Otherwise, implementation of the disposal standards may have effects quite different than those anticipated by EPA" (U.S. EPA, 1985, p. 38074). Chapter II documents the assumptions and interpretations of the Standard used in the WIPP assessment.

Containment Requirements

The primary objective of Subpart B is to isolate the waste from the accessible environment by limiting probabilities of long-term releases. This objective is reflected in § 191.13, the Containment Requirements.

PERFORMANCE ASSESSMENT

Quantitatively evaluating compliance with 191.13(a) requires a performance assessment, which has specific meaning within the Standard:

> "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))

The assessment as defined must provide a reasonable expectation that releases resulting from all significant processes and events that may affect the disposal system for 10,000 years after disposal have: (1) a likelihood of less than one chance in ten of exceeding quantities calculated as specified in Appendix A of the rule; and (2) a likelihood of less than one chance in 1,000 of exceeding ten times the specified quantities (§191.13(a)). Numerical limits have been placed not on the predicted cumulative radionuclide releases, but rather on the probability that cumulative releases will exceed quantities calculated as prescribed.

The term "performance assessment" has come to refer to the prediction of all long-term performance, because the performance assessment methodology, with minor modifications, can also be used to assess compliance with the 1,000-year performance. Henceforth, this report will refer to the assessment of compliance with both §191.13(a) of the Containment Requirements and the Individual Protection Requirements as the "performance assessment."

Qualitatively evaluating compliance (§191.13(b)) requires informed judgment by the DOE as to whether the disposal system can reasonably be expected to provide the protection required by §191.13(a). Thus, instead of relying on the performance assessment to <u>prove</u> that future performance of the disposal system will comply, DOE must examine the numerical predictions from the perspective of the entire record, and judge whether a reasonable expectation exists on that basis.

For the WIPP performance assessment, the disposal system consists of the underground repository, shafts, and engineered barriers, and the natural barriers of the disposal site. The engineered barriers are backfill in rooms; seals in drifts and panel entries; backfill and seals in shafts; and plugs in boreholes. Engineered modifications to the repository design could include making the waste a barrier. Natural barriers are the subsurface geology and hydrology within the controlled area. Barriers are not limited to the examples given in the Standard's definition, nor are those examples mandatory for the WIPP. As recommended by the EPA in Appendix B, "...reasonable projections for the protection expected from all of the engineered and natural barriers...will be considered." No portion will be disregarded, unless that portion of the system makes "negligible contribution to the overall isolation provided" by the WIPP (U.S. DOE, 1989a).

HUMAN INTRUSION

In the Second Modification to the Consultation and Cooperation Agreement, the DOE agreed to prohibit subsurface mining, drilling, slant drilling under the withdrawn area, or resource exploration unrelated to the WIPP Project on the sixteen square miles to be withdrawn under DOE control. The Standard clearly limits reliance on 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 because such controls could substantially reduce the probability of intrusion and improve predicted repository performance (Bertram-Howery and Swift, 1990).

The Containment Requirements consider a broad range of potential releases, but the most significant event to affect a disposal system within a salt formation will probably be human intrusion. The EPA stated that salt formations are easy to mine and are often associated with economic resources. Typical examples of human intrusion include but are not limited to exploratory drilling for any reason, mining, or construction of other facilities for reasons unrelated to the repository. Determining compliance with the Standard, therefore, requires performance assessments that include the probabilities and consequences of disruptive events, including potential human intrusion. The possibility of inadvertent human intrusion into repositories in salt formations because of resource evaluation must be considered, and the use of passive institutional controls to deter such intrusion should be accounted for in performance assessments (U.S. EPA, 1985, p. 38080).

The EPA gives specific guidance in Appendix B of the Standard for considering inadvertent human intrusion. The EPA believes that only realistic possibilities for human intrusion that may be mitigated by design, site selection, and passive institutional controls need be considered. Additionally, the EPA assumes that passive institutional controls should "...reduce the chance of inadvertent intrusion compared to the likelihood if no markers and records were in place." Exploring for subsurface resources requires extensive and organized effort. Because of this effort, information from passive institutional controls is likely to reach resource explorers and deter intrusion into the disposal system (U.S. EPA, 1985, p. 38080). In particular, as long as passive institutional controls "endure and are understood," the guidance states they can be assumed to deter systematic or persistent exploitation of the disposal site, and, furthermore, can reduce the likelihood of inadvertent, intermittent human intrusion. The EPA assumes that exploratory drilling for resources is the most severe intrusion that must be considered (U.S. EPA, 1985). Mining for resources need not be considered within the controlled area (Hunter, 1989).

Effects of the site, design, and passive institutional controls can be used in judging the likelihood and consequences of inadvertent drilling intrusion. The EPA suggests in Appendix B of the Standard that intruders will soon detect or be warned of the incompatibility of their activities with the disposal site by their own exploratory procedures or by passive institutional controls (U.S. EPA, 1985).

Four conclusions have been drawn by the WIPP performance-assessment team relative to human intrusion:

> No human intrusion of the repository will occur during the period of active institutional controls. Credit for active institutional controls can be taken for no more than 100 years after decommissioning. The performance assessment will assume active control for the first 100 years.
>
> While passive institutional controls endure, no deliberate resource exploration or exploitation will occur inside the controlled area, but reasonable, site-specific exploitation outside the controlled area may occur. The period of effective passive control will be factored into the performance assessment as soon as specifications for passive controls are developed.

> Intrusion into the repository leads to its detection. No mechanism for detection need be advanced. The EPA's use of the word "incompatibility" allows the conclusion that the intruders will plug and abandon their boreholes to avoid the effects of the repository.
>
> The number of exploratory boreholes assumed to be drilled inside the controlled area is to be based on site-specific information and need not exceed 30 boreholes/km^2 (0.4 mi^2) per 10,000 years. No more severe scenarios for human intrusion inside the controlled area need be considered. While passive institutional controls endure, the drilling rate assumed for inadvertent human intrusion will be significantly reduced, although the likelihood cannot be eliminated.

Given the approach chosen by the EPA for defining the disposal standards, repository performance must be predicted probabilistically to numerically 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. All approaches to assessing drilling probability presently being considered by SNL must include expert judgment (Bertram-Howery and Swift, 1990).

RELEASE LIMITS

Appendix A to the Standard establishes release limits for all regulated radionuclides. Table 1 in that appendix gives the limit for cumulative releases to the accessible environment for 10,000 years after disposal for each radionuclide per unit of waste. Note 1(e) to Table 1 defines the unit of waste as an amount of TRU wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years. Note 2(b) describes how to develop release limits for a TRU-waste disposal system: the release limits are the quantities in Table 1 multiplied by the units of waste. These waste units are treated as scaling factors. Note 6 describes the manner in which the release limits are to be used to determine compliance with § 191.13(a): for each radionuclide released, the ratio of the cumulative release to the total release limit for that radionuclide must be determined; ratios for all radionuclides released are then summed for comparison to requirements of § 191.13(a). Thus the quantity of a radionuclide that may be safely released depends on the quantities of all other nuclides projected to be released, but cannot exceed its own release limit. The summed normalized release cannot exceed 1 for probabilities greater than 0.1 and cannot exceed 10 for probabilities greater than 0.001, but less than 0.1. Potential releases estimated to have probabilities less than 0.001 are not limited.

For example, Table 1 in Appendix A to the Standard lists the release limits for plutonium-239 and americium-241 as 100 curies each per waste unit; for a repository with a waste unit of one and a release that contains only those two nuclides, the sum of the two must not be greater than 100 curies unless the probability of release is less than 0.1 and must not be greater than 1,000 curies unless the probability is less than 0.001. The smallest release limit in the table is 10 curies per waste unit for thorium-230 or -232; the largest release limit is 1,000 curies per waste unit for technitium-99. For the WIPP, the maximum possible waste unit for the stated capacity is about 15. All radioactivity in the waste cannot be included in the waste unit, however, because about half the radioactivity is from alpha-emitting transuranic radionuclides with half-lives less than 20 years, although certain daughter products of these omitted radionuclides are regulated. The waste unit for the WIPP will likely be about 6. Regardless of the waste unit, all regulated radionuclides must be included in release calculations, resulting in allowable releases that are artificially reduced by a factor of almost 3.

UNCERTAINTIES

The EPA recognized that Subpart B must be implemented in the design phase because active surveillance cannot be relied upon over the very long time of interest. The EPA also recognized that the Standard "must accommodate large uncertainties, including uncertainties in our current knowledge about disposal system behavior and the inherent uncertainties regarding the distant future" (U.S. EPA, 1985, p. 38070).

Performance assessment requires considering numerous uncertainties in the projected performance of the disposal system. The WIPP Project will use the interpretation of the EPA requirement for uncertainty analysis developed in previous work at SNL for high-level waste disposal (Cranwell et al., 1990; Pepping et al., 1983; Hunter et al., 1986; Cranwell et al., 1987; Campbell and Cranwell, 1988; Rechard, 1989). The EPA has explicitly recognized that performance assessments will contain uncertainties and that many of these uncertainties cannot be eliminated. For the WIPP, uncertainties will be parameter uncertainties, that is, uncertainties about the numerical values in or resulting from data, and uncertainties in the conceptual model and its mathematical representation. One type of uncertainty that cannot be completely resolved is the validity of various models for predicting disposal system behavior 10,000 years into the future. Although models will be validated to the extent possible, expert judgment must be relied upon where validation is not possible. In the case of competing conceptual models, if a single conceptual model cannot be demonstrated to be fully acceptable, or if more than one model adequately explains all known facts and complies with all applicable theoretical concepts, then multiple conceptual models will be developed and performance assessment calculations will incorporate each model as appropriate. Uncertainties arising from the numerical solutions of the mathematical model are resolved in the process of verifying computer programs. Completeness in scenario development or screening is most appropriately addressed through peer review and probability assignment (U.S. DOE, 1990a).

The WIPP Project will reduce uncertainty to the extent practicable using a variety of techniques (Table II-1). The techniques in Table II-1 are typically applied iteratively. The first iteration can include rather crude assumptions leading to preliminary results that help focus these techniques in subsequent iterations. In this manner, the resources required to implement the techniques in Table II-1 can be directed at the areas of the WIPP performance assessment where the benefits of reducing uncertainty would be the greatest.

The necessity of considering uncertainty in predicted behavior, projected performance, and estimates of cumulative releases is recognized in the Standard in § 191.12(p), § 191.12(q)(3), § 191.13(b), and in Appendix B (U.S. EPA, 1985). Parameter uncertainty is mentioned only in one paragraph in Appendix B, although parameter uncertainty is a major contributor to the other areas of uncertainty. Model uncertainty and scenario uncertainty are not mentioned at all, yet they could be even more important sources of uncertainty than the parameters. Although uncertainties must be addressed, no guidance is provided in the Standard as to how this is to be accomplished.

COMPLIANCE ASSESSMENT

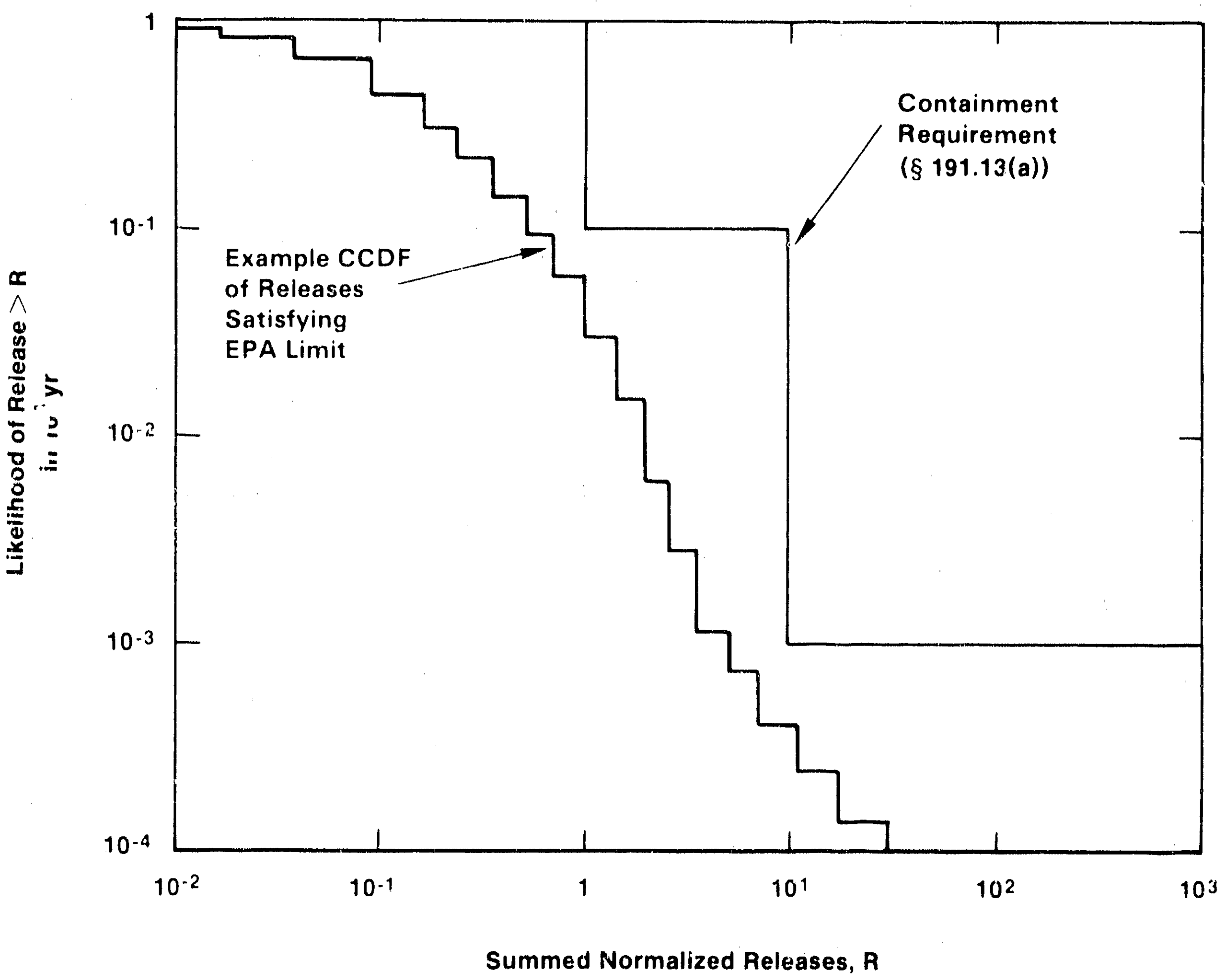
The Standard requires that the results of the performance assessment for § 191.13(a) be incorporated into an overall probability distribution of cumulative release to the extent practicable. In Appendix B, the EPA assumes that results can be assembled into a single complementary cumulative distribution function (CCDF) that indicates the probability of exceeding various levels of cumulative release (Figure II-1). The EPA assumes that this single curve will incorporate all parameter uncertainty, and if this single distribution function meets the requirement of § 191.13(a), then a disposal system can be considered to be in compliance with the Containment Requirements (U.S. EPA, 1985). Thus, EPA assumes that satisfying the numeric requirements is sufficient to demonstrate compliance with § 191.13(a) but

TABLE II-1. TECHNIQUES FOR ASSESSING AND REDUCING UNCERTAINTY IN THE WIPP PERFORMANCE ASSESSMENT

Type of Uncertainty	Technique for Assessing or Reducing Uncertainty
Scenarios (Completeness, Logic, and Probabilities)	Expert Judgment and Peer Review; Quality Assurance
Conceptual Models	Expert Judgment and Peer Review; Sensitivity Analysis; Quality Assurance
Computer Models	Expert Judgment and Peer Review; Verification and Validation*; Sensitivity Analysis; Quality Assurance
Parameter Values and Variability	Expert Judgment and Peer Review; Data-Collection Programs; Sampling Techniques; Sensitivity Analysis; Uncertainty Analysis; Quality Assurance

*to the extent possible
Source: Bertram-Howery and Hunter, 1989a

does not say it is absolutely necessary for demonstrating compliance. The EPA implies that a basis for concluding that a system provides good isolation exists that does not totally depend upon the calculated CCDF. The Containment Requirements (§ 191.13(a)) state that, based upon performance assessment, releases shall have probabilities not exceeding specified limits. Noncompliance is implied if the single CCDF suggested by the EPA exceeds the limits; however, § 191.13(b) states that performance assessments need not provide complete assurance that the requirements in § 191.13(a) 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. The likelihood that excess releases will occur must be considered in the qualitative decision about a "reasonable expectation" of compliance, but is not necessarily the deciding factor (Bertram-Howery and Swift, 1990).



TRI-6342-17-1

Figure II-1. Hypothetical CCDF Illustrating Compliance with the Containment Requirements (after Rechard, 1989).

MODIFYING THE REQUIREMENTS

The EPA acknowledged that implementation of the Containment Requirements might require modifying those standards in the future. This implementation

> ...will require collection of a great deal of data during site characterization, resolution of the inevitable uncertainties in such information, and adaptation of this information into probabilistic risk assessments. Although [EPA] is currently confident that this will be successfully accomplished, such projections over thousands of years to determine compliance with an environmental regulation are unprecedented. If--after substantial experience with these analyses is acquired--disposal systems that clearly provide good isolation cannot reasonably be shown to comply with the containment requirements, the [EPA] would consider whether modifications to Subpart B were appropriate.
>
> Another situation that might lead to suggested revisions would be if additional information were developed regarding the disposal of certain wastes that appeared to make it inappropriate to retain generally applicable standards addressing all of the wastes covered by this rule. (U.S. EPA, 1985, p. 38074)

In discussing the regulatory impacts of the Standard (U.S. EPA, 1985, p. 38083), the EPA acknowledged that no impact analysis was performed for TRU wastes. The EPA evaluated the costs of the various engineering controls potentially needed for <u>commercial</u> repositories to meet different levels of protection for the Containment Requirements and concluded additional precautions beyond those already planned were unnecessary. No such analysis was performed for the only defense waste repository, the WIPP.

Assurance Requirements

The EPA included Assurance Requirements (§ 191.14) in the 1985 Standard to provide confidence the agency believed is needed for long-term compliance with the Containment Requirements by disposal systems not regulated by the NRC. These requirements are designed to complement the Containment Requirements because of the uncertainties involved in predicting long-term performance of disposal systems (U.S. EPA, 1985, p. 38072).

The Assurance Requirements include six provisions: active institutional controls; monitoring after decommissioning to detect performance deviations; passive institutional controls; different types of barriers encompassing both engineered and natural barriers; avoidance of sites where a reasonable expectation of future resource exploration exists, unless favorable disposal characteristics compensate; and the possibility of removal of wastes for a reasonable period of time. Each Assurance Requirement applies to some aspect of uncertainty about long-term containment. Limiting reliance on active institutional controls to 100 years will reduce reliance on future generations to maintain surveillance. Carefully planned monitoring will mitigate against unexpectedly poor system performance going undetected. Markers and records will reduce the chances of systematic and inadvertent intrusion. Multiple barriers, both engineered and natural, will reduce the risk should one type of barrier not perform as expected. Considering future resource potential and publishing a finding that the favorable characteristics of the disposal site compensate for the likelihood of disturbance will add to the confidence that the Containment Requirements can be met. A system design that permits possible future recovery of the wastes for a reasonable period of time after disposal will allow future generations the option of relocating the wastes should new developments warrant such recovery (U.S. DOE, 1990a).

Individual Protection Requirements

The Individual Protection Requirements (§ 191.15) necessitate predicting potential doses to man resulting from releases to the accessible environment during the first 1,000 years after decommissioning of the repository, in the event that performance assessments predict such releases. Although challenges to this requirement contributed to the remand of Subpart B to the EPA, the WIPP Project cannot assume that the requirement will change when the Standard is repromulgated.

The methodology developed for assessing compliance with the Containment Requirements can be used to predict releases for estimating doses as specified by the Individual Protection Requirements. In predicting the undisturbed performance of the disposal system, variations from the design-basis (planned) behavior will reflect uncertainties in the numerical values of the design parameters and in the available data. The undisturbed performance of the repository is its design-basis behavior and reasonable variations in that behavior resulting from uncertainties in designing systems and components to function for 10,000 yrs. Undisturbed performance for the WIPP is understood to mean that uncertainties in such repository features as engineered barriers (backfill, seals, and plugs) must be specifically included in the analysis of the predicted behavior (U.S. DOE, 1990a).

> "Undisturbed performance" means predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. (§ 191.12(p))

Human intrusion means any human activity other than those directly related to repository characterization, construction, operation, or monitoring. The effects of intrusion are specifically excluded for the undisturbed performance analysis (U.S. DOE, 1989a).

Unlikely natural events at the WIPP will be those events and processes that have not occurred in the past at a sufficient rate to affect the Salado Formation at the repository horizon within the controlled area in such a way as to have caused the release of radionuclides, had they been present. Only the presence of groundwater has affected the Salado in the vicinity of the WIPP at the repository horizon for the past several million years. Therefore, the WIPP Project will model only groundwater flow and the effects of the repository as the undisturbed performance (U.S. DOE, 1989a). Because of the relative stability of the natural systems within the region of the WIPP disposal system, all naturally occurring events and processes that are expected to occur are part of the base-case scenario and are assumed to represent undisturbed performance (Marietta et al., 1989).

The EPA assumes in Appendix B of the Standard that compliance with § 191.15 "can be determined based upon best estimate predictions" rather than a CCDF. Thus, according to the EPA, when uncertainties are considered, only the mean or median of the appropriate distributions, whichever is greater, need fall below the limits.

The Individual Protection Requirements limit the annual dose equivalent from the disposal system to any member of the public in the accessible environment to 25 millirems to the whole body or 75 millirems to any critical organ. These requirements apply to undisturbed performance of the disposal system, considering all potential release and dose pathways for 1,000 years after disposal. One of the requirements is that modeled individuals be assumed to consume 2 ℓ (0.5 gal)/day of drinking water from a significant source of groundwater, which is specifically defined in the Standard.

> "Significant source of ground water" ... means: (1) An aquifer that: (i) Is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface; (iii) has a transmissivity greater than 200 gallons per day per foot, provided that any formation or part of a formation included within the source of groundwater has a hydraulic conductivity greater

> than 2 gallons per day per square foot ...; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of [November 18, 1985]. (§ 191.12 (n))

No water-bearing unit at the WIPP meets the first definition of significant source of groundwater everywhere because dissolved solids exceed 10,000 mg/ℓ and transmissivity is minimal in most places (Mercer, 1983); however, the WIPP Project will assume that any portion of an aquifer that meets the first definition is a significant source of groundwater. Communication between non-qualifying and qualifying portions will be evaluated. No community water system is being supplied by any aquifer near the WIPP, therefore no aquifer meets the second definition of significant source of groundwater (U.S. DOE, 1989a).

The Dewey Lake Red Beds are saturated only in some areas. Neither the Magenta Dolomite Member nor the Culebra Dolomite Member of the Rustler Formation (Figure I-5) appears to be a significant source of groundwater. Aquifers below the Salado Formation are more than 762 m (2,500 ft) below the land surface at the WIPP. The nearest aquifer that meets the first definition of a significant source of groundwater over its entire extent is the alluvial and valley-fill aquifer along the Pecos River. Communication between this aquifer and any other aquifers in the vicinity of the WIPP will be evaluated (U.S. DOE, 1989a).

No releases from the repository/shaft system are expected to occur within 1,000 years (Lappin et al., 1989; Marietta et al., 1989); therefore, dose predictions for undisturbed performance could be unnecessary. To date, analyses of undisturbed conditions suggest successful long-term isolation of the waste.

Groundwater Protection Requirements

Special sources of groundwater are protected from contamination at levels greater than certain limits by the Groundwater Protection Requirements (§ 191.16). There are no special sources of groundwater at the WIPP; therefore, the requirement to analyze radionuclide concentrations in such groundwater is not relevant to the WIPP (see Chaper IX).

III. COMPLIANCE ASSESSMENT PHILOSOPHY AND METHODOLOGY OVERVIEW

The text of Chapter III is preceded by a synopsis that simplifies concepts presented in Chapter III. Detailed information about those concepts is in the text following the synopsis.

Synopsis

Philosophy of the WIPP Compliance Assessment

The WIPP compliance assessment is based on four ideas:

> A performance assessment must determine the events that can occur (scenario development), the likelihood of those events, and the consequences of those events.
>
> The impact of uncertainties must be characterized and displayed because uncertainties will always exist in the results of a performance assessment.
>
> No single summary measure can adequately display all the information produced in a performance assessment. Decisions on the acceptability of the WIPP must be based on a careful consideration of all available information, including qualitative information not in the calculations.
>
> Adequate documentation and independent peer review are essential parts of the performance assessment and supporting research.

The Containment Requirements

The Containment Requirements specify that performance assessments must be used to determine whether cumulative releases to the accessible environment for 10,000 years after disposal will meet certain probability limits.

The Containment Requirements establish the limits (191.13(a)) and temper the limits with qualitative considerations (191.13(b)). Appendix B to Subpart B of the Standard describes how compliance can be determined quantitatively by using a complementary cumulative distribution function (CCDF).

The construction of CCDFs follows naturally from the development of scenario probabilities and the calculation of scenario consequences. Further, the effects of uncertainties can be shown by constructing families of CCDFs and then reducing each family to a single mean CCDF.

Single-scenario CCDF curves are used extensively in performance-assessment sensitivity analysis for comparing various intermediate results in the modeling process. Such CCDF curves do not establish compliance or noncompliance, but they convey vital information about how changes in selected model parameters may influence performance and compliance.

No "final" CCDF curves yet exist. Because probabilities for specific scenarios and many parameter-value distribution functions are still undetermined, all CCDF curves presented in this report are preliminary.

Individual Protection Requirements

The scenario for undisturbed conditions and the methods developed for the Containment Requirements can be used to predict releases to the accessible environment during the first 1,000 years after closure. Dose estimates can be made using releases predicted, if any.

Overview of Methods for WIPP Performance Assessment

The manner in which radionuclides migrate away from the repository is simulated with a collection of techniques and computer programs that estimates quantities of radionuclides that could be released to the accessible environment.

The procedures include

Characterizing the disposal system and the region.

Developing scenarios.

Modeling consequences with complex computer programs.

Scenarios

The need for developing scenarios is not stated in the Standard but is implied in the Containment Requirements.

Scenario development provides a means for analysis of uncertainty in future states of the disposal system.

Uncertainty is represented by developing a probability distribution for occurrence of the scenario.

The goal of scenario development is a comprehensive set of mutually exclusive scenarios that could result in the release of radionuclides to the accessible environment.

Scenarios that significantly affect the groundwater-flow regime are usually analyzed individually to identify important parameters and examine the scenario's effect on the conceptual model.

Compliance Assessment System

The physical processes simulated in consequence modeling include

Groundwater flow and radionuclide transport in the natural barrier system.

Repository resaturation from brine inflow.

Gas generation from waste and container decomposition and from radiolysis of brine and waste.

Room closure from salt creep.

Radionuclide transport in rooms, drifts, interbeds, and shafts in the repository/shaft system.

Borehole intrusion through these systems must also be simulated for the Containment Requirements.

For the Individual Protection Requirements, radionuclide transport to and dispersion in the surface and near-surface are also included.

Model verification means ensuring that the computer program implementing the model correctly performs the operations specified in the numerical procedures.

Model validation means checking physical correctness to the extent possible.

Few models that describe environmental systems can ever be fully validated for the space and time scales of interest; model adequacy for a particular application relies on the subjective judgment of the analyst, as endorsed by appropriate expert reviewers.

CAMCON

The compliance assessment system, a modular system of computer programs controlled by a master program, is referred to as the "Compliance Assessment Methodology Controller" (CAMCON).

CAMCON consists of individual computer programs that can perform different types of assessments of WIPP data; CAMCON contains additional programs that automatically translate the results of one computer program into the format used by subsequent programs.

CAMCON can therefore perform computations through a large set of programs with little operator intervention.

The three data bases in CAMCON are strictly controlled to assure data quality.

Features within CAMCON attempt to guarantee reproducibility for each computation and minimize human error.

Uncertainty Analysis

The models being used for the WIPP performance assessment are generally complex, and the results of the consequence estimates have large uncertainties associated with them because of model and data uncertainty.

Risk

Uncertainties can be evaluated mathematically by placing them in a risk framework.

Risk is simply perceived in terms of what can go wrong, how likely things are to go wrong, and what the consequences are of things going wrong.

Risk results are often summarized with complementary cumulative distribution functions (CCDFs), which are graphical methods of representing the probabilities that consequence values will be exceeded.

In performance assessments for radioactive waste disposal, the consequence results of greatest interest are usually cumulative releases calculated as specified in Appendix A to the EPA Standard. The EPA Standard places restrictions on certain points on the CCDF for these releases and associated probabilities.

Uncertainty in Risk

A number of factors affect the uncertainty in risk results, including completeness, aggregation, model selection, imprecisely known variables, and stochastic variation.

Completeness refers to the extent that a performance assessment includes all possible occurrences for the disposal system under consideration (e.g., low-probability scenarios are screened out).

Aggregation refers to the division of the possible occurrences into scenarios and thus relates to the logic used in the construction of the scenarios.

Model selection refers to the actual choice of the models used in a risk assessment (e.g., for some processes, alternative models can exist).

Imprecisely known variables can be such parameters as solubility limits.

Stochastic variation is represented by probabilities that are functions of the many factors that affect the individual scenarios.

Characterizing Uncertainty in Risk

The uncertainty in the results of a particular performance assessment depends on exactly what result of the performance assessment is of concern.

In most assessments, CCDFs are the results of greatest interest.

One type of uncertainty that is often of interest is the variation in the CCDF due to imprecisely known variables.

Another type of uncertainty that is of concern is the variation in estimates for mean CCDFs and other statistical summaries that result from imprecisely known variables.

Risk and the EPA Limits

If the probabilities and consequences associated with a given scenario were known with certainty, than a single CCDF could be constructed for comparison with the EPA limits.

Because neither probabilities nor consequences are known with certainty, a vector of imprecisely known variables is used to estimate the probabilities and consequences.

A CCDF can be constructed for each sample element and consequence measure contained in the set of scenario consequences, and all can be drawn on a single plot as a family of CCDFs. A particular curve would be the appropriate choice for comparison against the EPA requirements only if the variable values for probability and consequence used to construct that CCDF were the correct ones.

Mean and percentile curves can be used to summarize the family of CCDFs instead of a plot cluttered with many individual curves. The mean curve has generally been proposed for showing compliance with § 191.13(a) and is the primary summary measure in the performance assessments for the WIPP.

Preliminary analyses for § 191.13(a) have typically assumed that the individual scenario probabilities are known with certainty and that the only uncertainties in the analysis relate to the manner in which the cumulative release required for comparison with the EPA Standard is calculated.

Monte Carlo Techniques

Formal techniques for uncertainty and sensitivity analyses provide a systematic way to determine the impact of analysis assumptions on analysis results.

A Monte Carlo analysis is based on performing multiple model evaluations with probabilistically selected model input, and then using the results of these evaluations to determine both the uncertainty in model predictions and the input variables that give rise to this uncertainty.

The WIPP performance assessment has selected Monte Carlo analysis as the primary approach for performing formal uncertainty and sensitivity analyses because

> Monte Carlo techniques are particularly appropriate for analysis problems in which large uncertainties are associated with the independent variables.
>
> Distribution functions must often be estimated (such as for comparison with the EPA Standard).
>
> Monte Carlo techniques seldom require modifying the original model or adding numerical procedures.
>
> Monte Carlo techniques can be used to propagate uncertainties through a sequence of separate models.
>
> Monte Carlo techniques create a mapping from analysis input to analysis results.

The Performance Assessment Process

Performance assessment is a dynamic process that relies on iterative simulations using techniques and data developed as work progresses.

Neither the data base nor the models are fixed, and all aspects of the compliance assessment system are subject to review as new information becomes available.

Sensitivity analyses identify aspects of the modeling system where variability and uncertainty have the greatest potential to affect performance, thereby helping guide ongoing research.

Sensitivity analyses are being performed for each scenario that appears to be of regulatory interest.

Sensitivity analysis can be performed on individual components, the subsystem, or the system as a whole.

Results in this *1990 Preliminary Comparison* reflect improvements made during the previous year.

This *1990 Preliminary Comparison* presents a snapshot of a system that will continue to evolve until the final *Comparison* is complete.

The long-term probabilistic performance requirements of Subpart B of the Standard are the focus of this report. For the WIPP, two requirements must be met. The Containment Requirements (§ 191.13(a)) limit probabilities of cumulative releases of radioactive materials to the accessible environment for 10,000 years. The Individual Protection Requirements (§ 191.15) limit radiation doses to members of the public in the accessible environment for 1,000 years. The philosophy for assessing compliance of the WIPP with these requirements is discussed in this chapter, and the WIPP methodology for performing this assessment is described.

Philosophy

The WIPP compliance assessment for Subpart B is based on four ideas. First, a performance assessment must determine the events that can occur, the likelihood of these events, and the consequences of these events. Determining the possible events is commonly referred to as scenario development. In general, each scenario will be a collection of similar events that could possibly occur at the WIPP. Similarly, determining the likelihood of events happening assigns probabilities to these scenarios. These probabilities characterize the likelihood that individual scenarios will occur at the WIPP. Determining consequences requires calculating cumulative radionuclide releases or possibly human radiation exposures for individual scenarios. In most cases, such calculations require complex computer models.

Second, as uncertainties will always exist in the results of a performance assessment, the impact of these uncertainties must be characterized and displayed. Thus. uncertainty analysis and sensitivity analysis are important parts of a performance assessment. Uncertainty analysis attempts to characterize the uncertainty in analysis outcomes that results from uncertainty in the information on which the analysis is based. Sensitivity analysis attempts to determine the impact that specific information has on the final outcome of an analysis.

Third, no single summary measure can adequately display all the information produced in a performance assessment. Thus, decisions on the acceptability of the WIPP, or any other complex system, must be based on a careful consideration of all available information rather than on a single summary measure. To facilitate informed decisions as to whether "reasonable expectations" exist for the WIPP to comply with Subpart B, the WIPP performance assessment will generate and present detailed analysis results. Consideration of these results must also include any available qualitative information as prescribed in § 191.13(b).

Fourth, adequate documentation is an essential part of a performance assessment. Obtaining independent peer review and successfully communicating with interested parties requires careful documentation. An extensive effort, therefore, is being devoted to documenting and peer reviewing the WIPP performance assessment and the supporting research, including techniques, models, data, and analyses. Without adequate documentation, informed judgments on the suitability of WIPP as a waste repository are not possible.

The EPA requirements for radionuclide containment and individual radiation protection drive the performance assessment. The philosophy behind the approach for these two requirements is briefly discussed.

THE CONTAINMENT REQUIREMENTS

The Standard (§ 191.13(a)) requires that performance assessments be used to determine whether cumulative releases to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system will meet specific probability limits (U.S. EPA, 1985). Whereas no specific requirements are indicated as to how compliance is to be shown, Appendix B to Subpart B of the Standard describes how EPA assumes compliance can be determined with a CCDF. The guidance in Appendix B will be followed to the extent possible.

Descriptions of the procedure for performance assessment based on the construction of a CCDF are available (Cranwell et al., 1990; Pepping et al., 1983; Hunter et al., 1986; Cranwell et al., 1987; Campbell and Cranwell, 1988; and Rechard, 1989). The construction of CCDFs follows naturally from the development of scenario probabilities and the calculation of scenario consequences. Further, the effects of uncertainties can be shown by constructing families of CCDFs and then reducing each family to a single mean CCDF. The construction of CCDFs is described later in this chapter.

At present, single-scenario CCDF curves are used extensively in performance-assessment sensitivity analysis for comparing various intermediate results in the modeling process. Such CCDF curves do not establish compliance or noncompliance, but they convey vital information about how changes in selected model parameters may influence performance and compliance (Bertram-Howery and Swift, 1990).

No "final" CCDF curves yet exist. Because probabilities for specific scenarios and many parameter-value distribution functions are still undetermined (see Chapters IV and V), all CCDF curves presented in Chapter VI are preliminary. Although the compliance limits are routinely included on all plots as reference points, the currently available curves cannot be used to judge compliance with the Containment Requirements because the curves reflect an incomplete modeling system and incomplete data and because the Standard has not been repromulgated.

THE INDIVIDUAL PROTECTION REQUIREMENTS

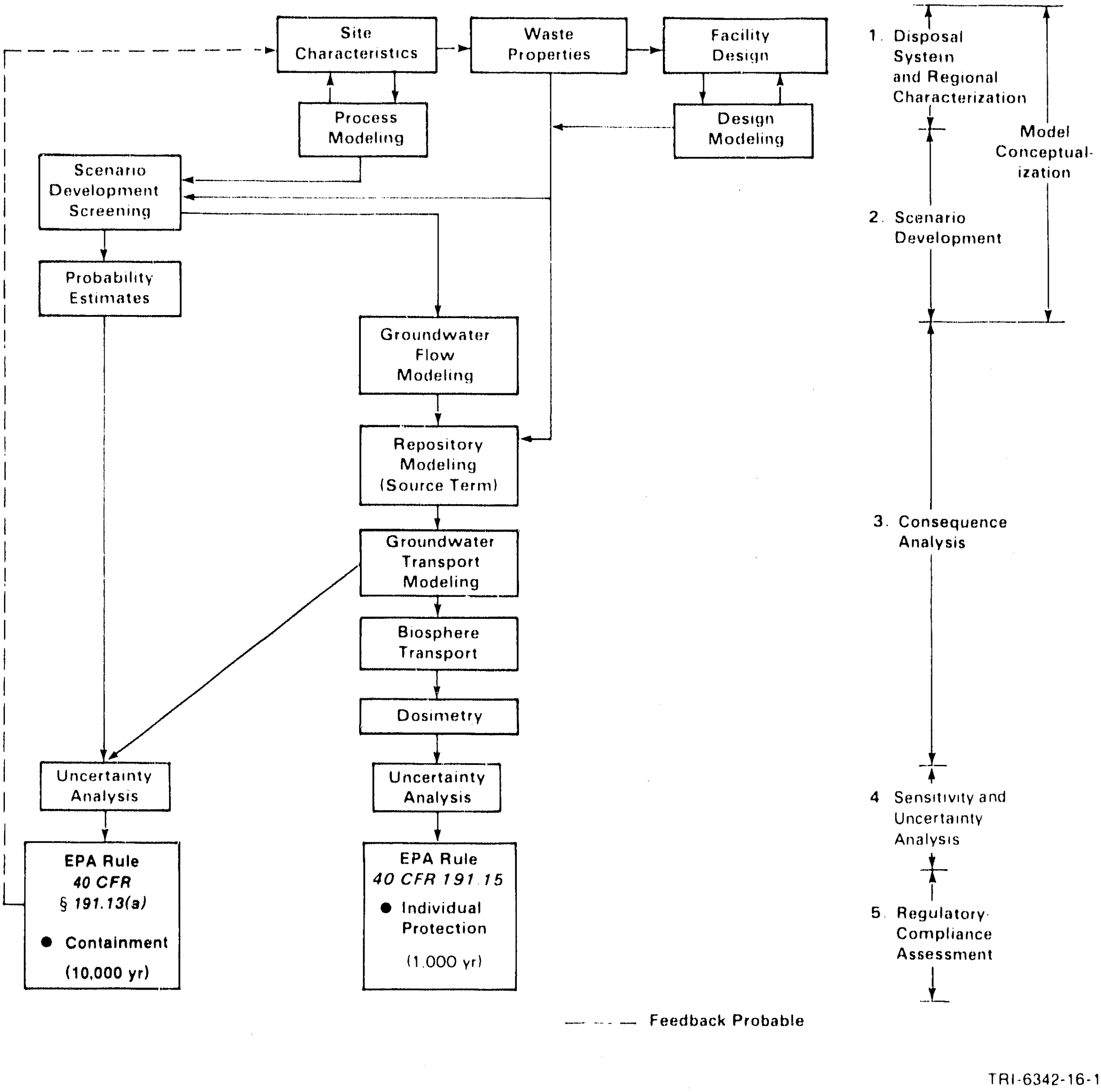
The Standard (§ 191.15) requires that annual, whole-body and critical-organ doses be predicted for radionuclide releases to the accessible environment from all pathways assuming undisturbed conditions during the first 1,000 years after disposal. One of the products of scenario development for the Containment Requirements will be a scenario for undisturbed conditions. The techniques for analyzing releases from the disposal system for this scenario will be available through the methodology developed for the Containment Requirements. If releases to the accessible environment are predicted to occur during the first 1,000 years after closure, compliance with the dose limits will be evaluated by using pathway and dosimetry models to predict doses associated with the predicted releases.

Methodology Overview

The WIPP compliance assessment methodology comprises the procedures and tools necessary for implementing the compliance assessment philosophy. Migration of radionuclides from the repository is estimated by applying a collection of techniques and computer programs in the methodology. The methodology requires characteristics of the disposal system and the region, techniques for scenario development and probability estimates, computer programs for consequence modeling, statistical techniques for uncertainty and sensitivity analyses, and procedures that assemble results into a CCDF for § 191.13(a) or determine the dose for § 191.15.

The methodology (Figure III-1) builds on previous work at SNL for high-level-waste disposal in hypothetical repositories in bedded salt (Cranwell et al., 1987) and basalt (Bonano et al., 1988). It also builds on work done at SNL in collaboration with the international Nuclear Energy Agency of the Organization for Economic and Cooperative Development (NEA, 1988) to analyze empirical data for potential subseabed repositories.

The first step in the analysis is describing the disposal system. Characteristics of the controlled area, the repository/shaft system, and the waste are investigated and described (Bertram-Howery and Hunter, 1989a; U.S. DOE, 1990c). Based on this disposal system description, those events and processes that are most likely to contribute to migration of radionuclides from the repository/shaft system and transport to the accessible environment



3 Figure III-1. Compliance Assessment Methodology Structure (after Rechard, 1989).

are identified and screened. Once these events and processes have been developed into scenarios and these scenarios have been screened based on physical reasonableness and probability, a system of models is used to estimate the consequence of each remaining scenario (Figure III-2).

SCENARIOS

Scenarios are sets of naturally occurring, human-induced or waste-induced conditions that represent realistic potential future states of the repository, the geologic systems, and the groundwater flow systems that could affect the migration and transport of radionuclides from the repository to the accessible environment (Cranwell et al., 1990). Whereas the Standard does not mention "scenarios" as such, the need for their development is implied in § 191.13(a).

Scenario development provides a means for analysis of uncertainty in future states of the disposal system. Uncertainty in the events and processes that make up a scenario is represented by the analyst assigning a probability distribution for the occurrence of each event or process to represent the state of knowledge. The probability of occurrence of the scenario is derived from the constituent events and processes. These constituent probability distributions are determined by expert judgment when data is insufficient to calculate probability distributions. Scenario development and probability assignment are discussed in Chapter IV.

The goal of the scenario-development procedure is to develop a comprehensive set of mutually exclusive scenarios that could result in the release of radionuclides to the accessible environment. To initiate an analysis, the physical processes being modeled are carefully defined, and multi-dimensional conceptual and mathematical models are developed that adequately describe the processes over the range of conditions to be modeled. For these models to be credible, phenomena and parameters that are determined by sensitivity analyses to be important to the performance measure must be included.

Scenarios that significantly affect the groundwater-flow regime are usually analyzed individually to identify important parameters and examine the scenario's affect on the conceptual model. (Sensitivity analyses are seldom performed for less-significant scenarios.) These single-scenarios sensitivity analyses may use complex, two- or three-dimensional models of groundwater flow and transport. When the flow behavior and other parameters are better understood, simpler models of flow and transport and other processes that mimic the predicted behavior can be substituted for use in subsequent, repetitive uncertainty analyses, for the complete set of scenarios.

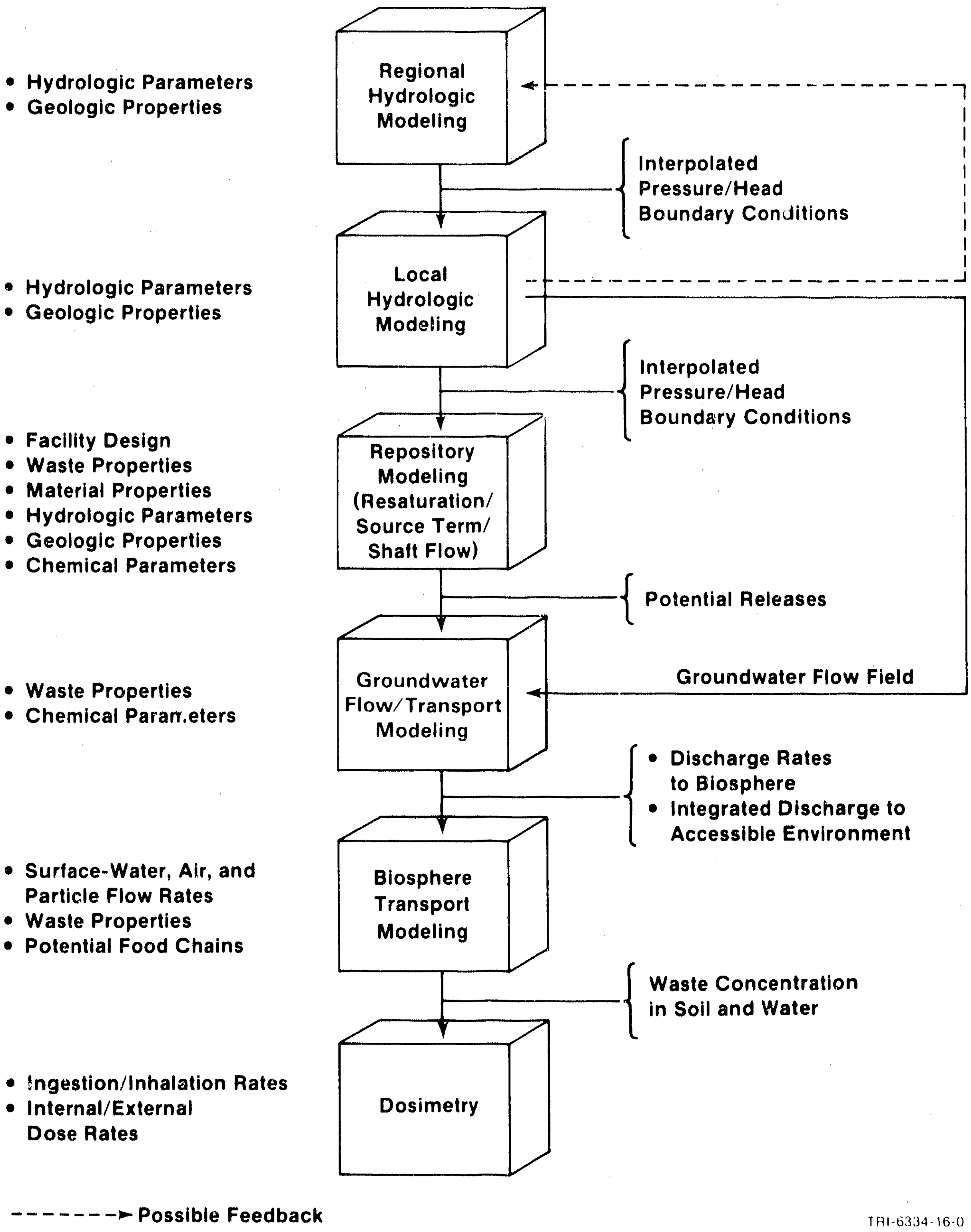


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Figure III-2. A System of Models for Consequence Analysis (Rechard, 1989).

COMPLIANCE ASSESSMENT SYSTEM

The physical processes simulated in consequence modeling include groundwater flow and radionuclide transport in the natural barrier system; repository resaturation from brine inflow, gas generation from waste and container decomposition and from radiolysis of brine and waste, room closure from salt creep, and radionuclide transport in rooms, drifts, interbeds, and shafts in the repository/shaft system. Borehole intrusion through these systems must also be simulated.

Groundwater flow is simulated at regional and local scales. The Los Medaños regional and local models are coupled through boundary conditions that are passed from regional to local models. For calibration, each model can provide boundary conditions to the other. These hydrologic models provide flow fields necessary for calculating radionuclide transport to the accessible environment where the cumulated release of each radionuclide can be obtained by integrating the discharge rate over 10,000 years.

For the Individual Protection Requirements, the biosphere transport code simulates the movement of radionuclides through the surface and near-surface environment and uptake by humans. This information is then used to estimate the whole-body and critical-organ doses.

For the Containment Requirements, comparison with the Standard can be made by a probability versus consequence curve in the form of a CCDF. Because consequence models currently being considered for use in the WIPP performance assessment are deterministic models, the uncertainty of input data can be incorporated into the analysis through Monte Carlo sampling of these data.

In principle, models used for performance assessment can be either deterministic or stochastic. Deterministic models do not explicitly account for uncertainties, whereas stochastic models may. The models in the WIPP performance assessment are all deterministic, because stochastic models incorporating the many processes affecting performance of the WIPP disposal system would be too complex to develop and use effectively. Monte Carlo sampling techniques are used to perform stochastic analysis with systems of deterministic models. Many stochastic processes that are known to be unimportant in the overall analysis are not included in the sampling, but are included in models through deterministic assumptions.

Important aspects of model development and application are model verification and validation. Verification ensures that the model correctly performs the operations specified in the numerical procedures. Verification does not assess the physical correctness of the solution; therefore, a model is verified when it numerically solves the specified problem correctly. Model validation addresses physical correctness. Validation usually involves a test of the model output against available data to ensure that the model is an adequate representation of natural processes or systems for which it is intended. Such tests evaluate both the mathematical model and related conceptual models. Few models that describe environmental systems can ever be fully validated on the space and time scales of interest. Rather, model adequacy for the particular application is a subjective judgment of the analyst based on partial validation exercises.

The compliance assessment system is a modular system of computer programs controlled by a computerized executive package. This system is referred to as the "Compliance Assessment Methodology CONtroller" (CAMCON). CAMCON contains translators that automatically translate the output of one computer program into the appropriate input format for the next program. In this way, the executive controller can perform a computation for m input vectors through the entire set of modules with little operator intervention.

CAMCON contains three data bases that are strictly controlled for quality-assurance (QA) purposes. The primary data base comprises observational data in a reduced form that are transformed, by interpolating or with optimal-estimation algorithms or by expert judgment, into a secondary data base that can be accessed by the executive controller. Transformation of primary data to secondary data is carefully quality controlled. While calculating cumulative release, the executive controller creates a computational data base that is generated anew for each input vector.

An important feature of CAMCON is that QA of calculations, data manipulation, and file management is explicitly included and automatically controlled. This QA process attempts to guarantee reproducibility for each computation and minimizes human error. QA for the performance assessment is included in the SNL QA program for the WIPP Project (SNL, 1988).

The compliance assessment is discussed in Chapter V.

UNCERTAINTY ANALYSIS

The physical processes by which radioactive material can be released to the accessible environment from the disposal system are complex. As a result, the WIPP performance assessment is commensurately complex, and consequence estimates have large uncertainties associated with them. This section examines a mathematical basis for evaluating those uncertainties by placing them in a risk framework. The discussion is adapted from Helton (1990).

Risk

Understanding risk and uncertainty in risk is facilitated by a clear conceptual representation for risk. Risk is often defined as consequence times probability or consequence times frequency. This definition, however, neither captures the nature of risk as perceived by most individuals nor provides much conceptual guidance on how risk calculations should be performed. Simply put, people are more likely to perceive risk in terms of what can go wrong, how likely things are to go wrong, and what the consequences are of things going wrong. The latter description provides a structure with which risk can be both represented and calculated.

Kaplan and Garrick (1981) have proposed representing risk with sets of ordered triples. Specifically, they propose that risk be represented by a set R of the form

$$R = \{(S_i, pS_i, \mathbf{cS}_i), i=1, \ldots, nS\}, \qquad \text{(III-1)}$$

where

S_i = a set of similar occurrences,

pS_i = probability that an occurrence in set S_i will take place,

$\mathbf{cS}_i$ = a vector of consequences associated with S_i,

nS = number of sets selected for consideration,

and the sets S_i have no occurrences in common (i.e., the S_i are disjoint sets). This representation formally decomposes risk into what can happen (the S_i), how likely things are to happen (the pS_i), and what the consequences are of a particular set of occurrences (the $\mathbf{cS}_i$). The S_i are typically referred to as "scenarios" in radioactive waste disposal. Similarly, the pS_i are scenario probabilities, and the vector $\mathbf{cS}_i$ contains environmental releases for individual isotopes, the normalized EPA release summed over all isotopes, and possibly other transport information associated with scenario S_i.

Although the representation in Equation III-1 provides a naturally conceptual way to view risk, the set R by itself can be difficult to examine. For this reason, the risk results in *R* are often summarized with complementary cumulative distribution functions (CCDFs). These functions provide a display of the information contained in the probabilities pS_i and the consequences $\mathbf{cS}_i$. With the assumption that a particular consequence result cS in the vector **cS** has been ordered so that $cS_i \le cS_{i+1}$ for i-1, ..., nS, the CCDF for this consequence result is the function F defined by

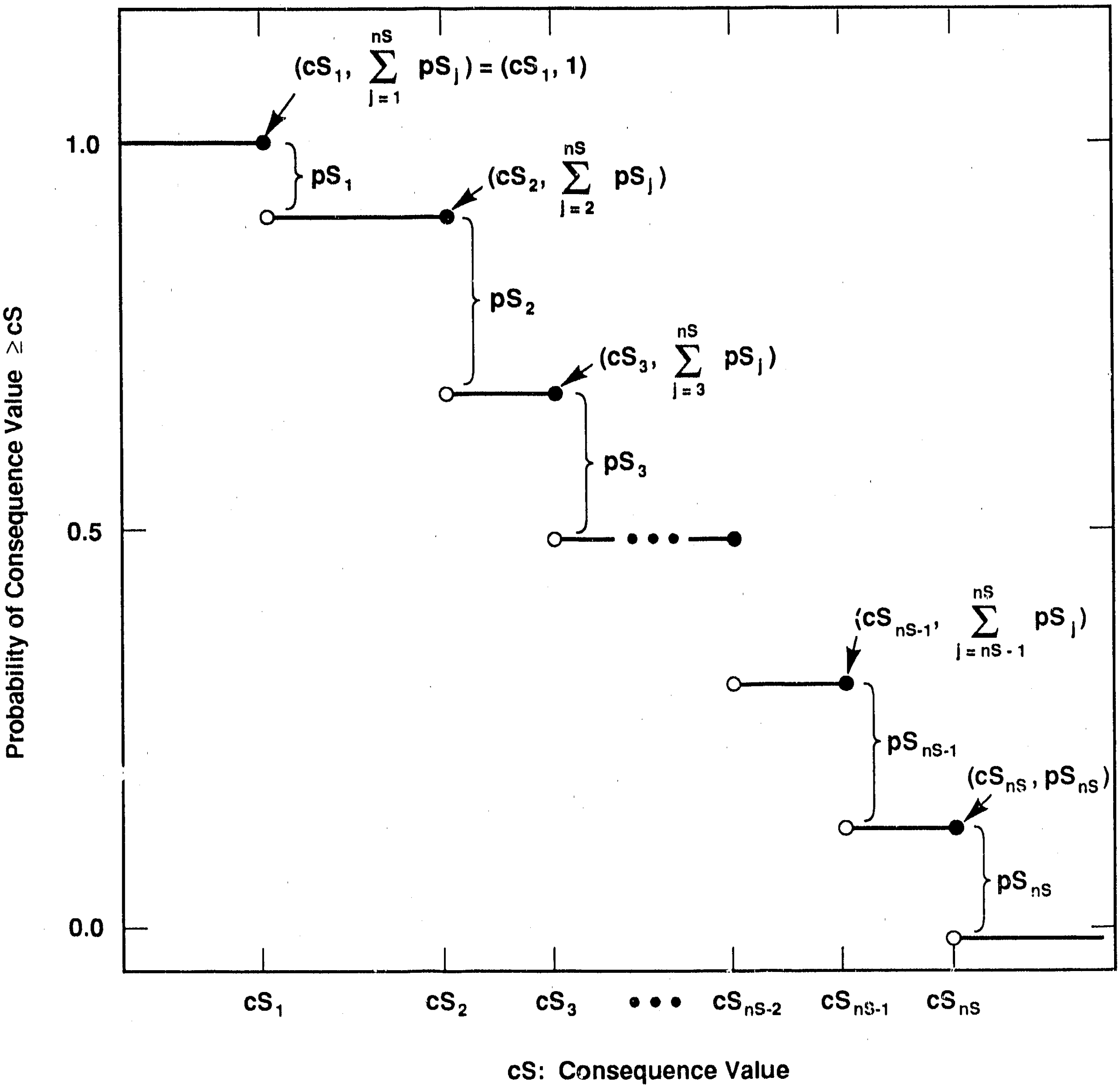
$$F(x) = \text{probability that cS exceeds a specific consequence value x}$$

$$= \sum_{j=i}^{nS} pS_j, \qquad \text{(III-2)}$$

where i is the smallest integer such that $cS_i \ge x$. As illustrated in Figure III-3, F is a step function that represents the probabilities that consequence values on the abscissa will be exceeded. Thus, "exceedance probability curve" is an alternate name for a CCDF and is more suggestive of the information that it displays. To avoid a broken appearance, CCDFs are often plotted in the form shown in Figure III-4, which is the same as Figure III-3 except that vertical lines have been added at the discontinuities.

The steps in the CCDFs shown in Figure III-3 and Figure III-4 result from the discretization of all possible occurrences into the sets S_1, ..., S_{nS}. Unless the underlying processes are inherently disjoint, the use of more sets S_i will tend to reduce the size of these steps and, in the limit, will lead to a smooth curve. Thus, Equation III-2 really defines an estimated CCDF. Better estimates can be obtained by using more sets S_i and also by improving the estimates for pS_i and $\mathbf{cS}_i$. However, various constraints, including available information and computational cost, will always limit how far such efforts can be carried.

In performance assessments for radioactive waste disposal, the consequence result of greatest interest is usually the EPA sum of normalized releases. This sum is simply one of many predicted quantities that could be the variable on the abscissa in Figure III-3 and Figure III-4. The normalized release, however, is special in that the Standard places restrictions on certain points on the CCDF for this release. As illustrated in Figure III-5, the probabilities of exceeding 1 and 10 are required to be less than 0.1 and 0.001, respectively. The CCDF in Figure III-5 is drawn as a smooth curve, which is the limiting case for a large number of scenarios. If the number of scenarios is small, then the CCDF for the normalized sum will resemble the step functions shown in Figure III-3 and Figure III-4.



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3 Figure III-3. Estimated CCDF for Consequence Result cS (Helton, 1990).

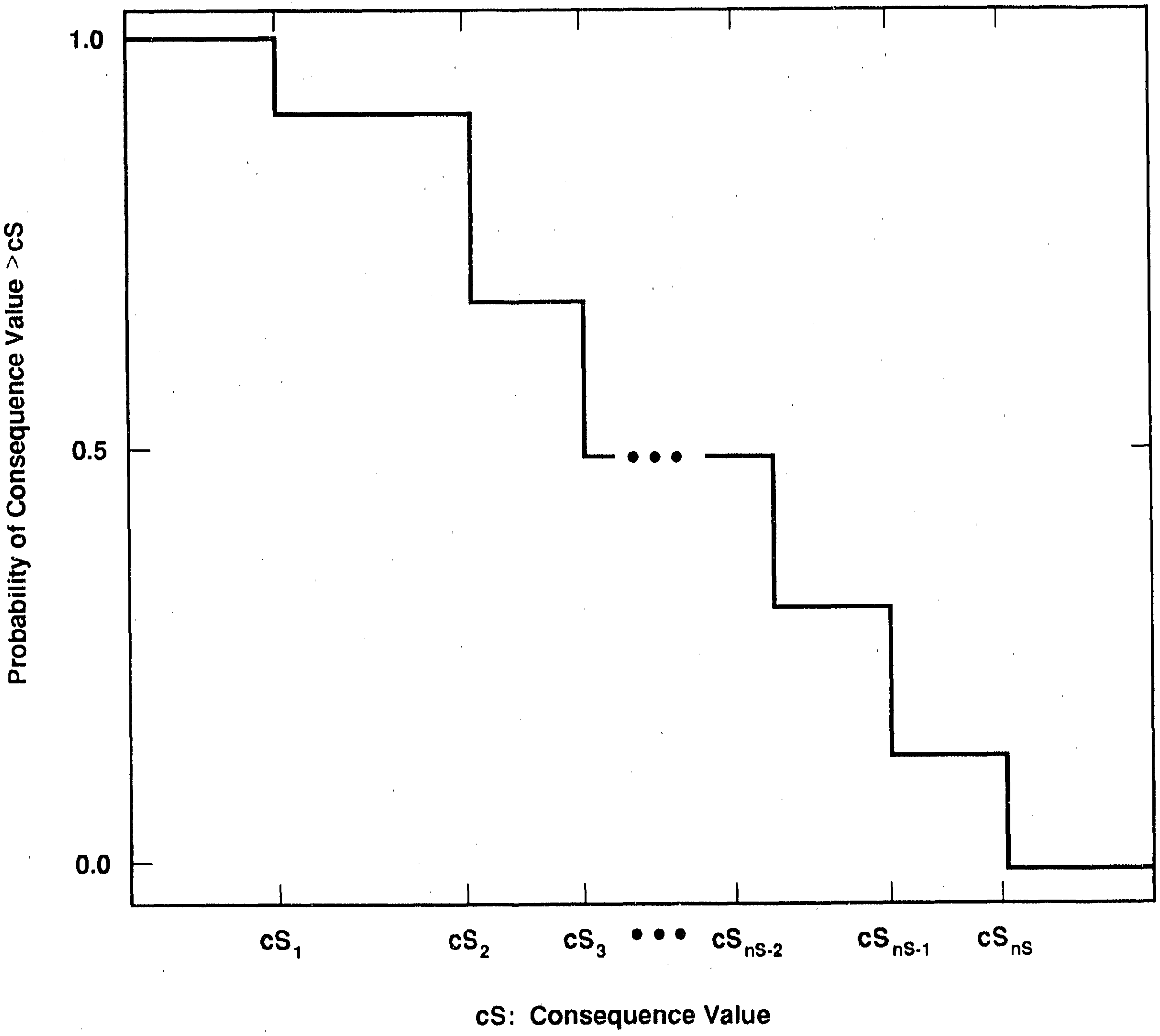

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Figure III-4. Estimated CCDF for Consequence Result cS Including Vertical Lines at the Discontinuities. This figure is the same as Figure III-3 except for the addition of the vertical lines at the discontinuities. (Helton, 1990).

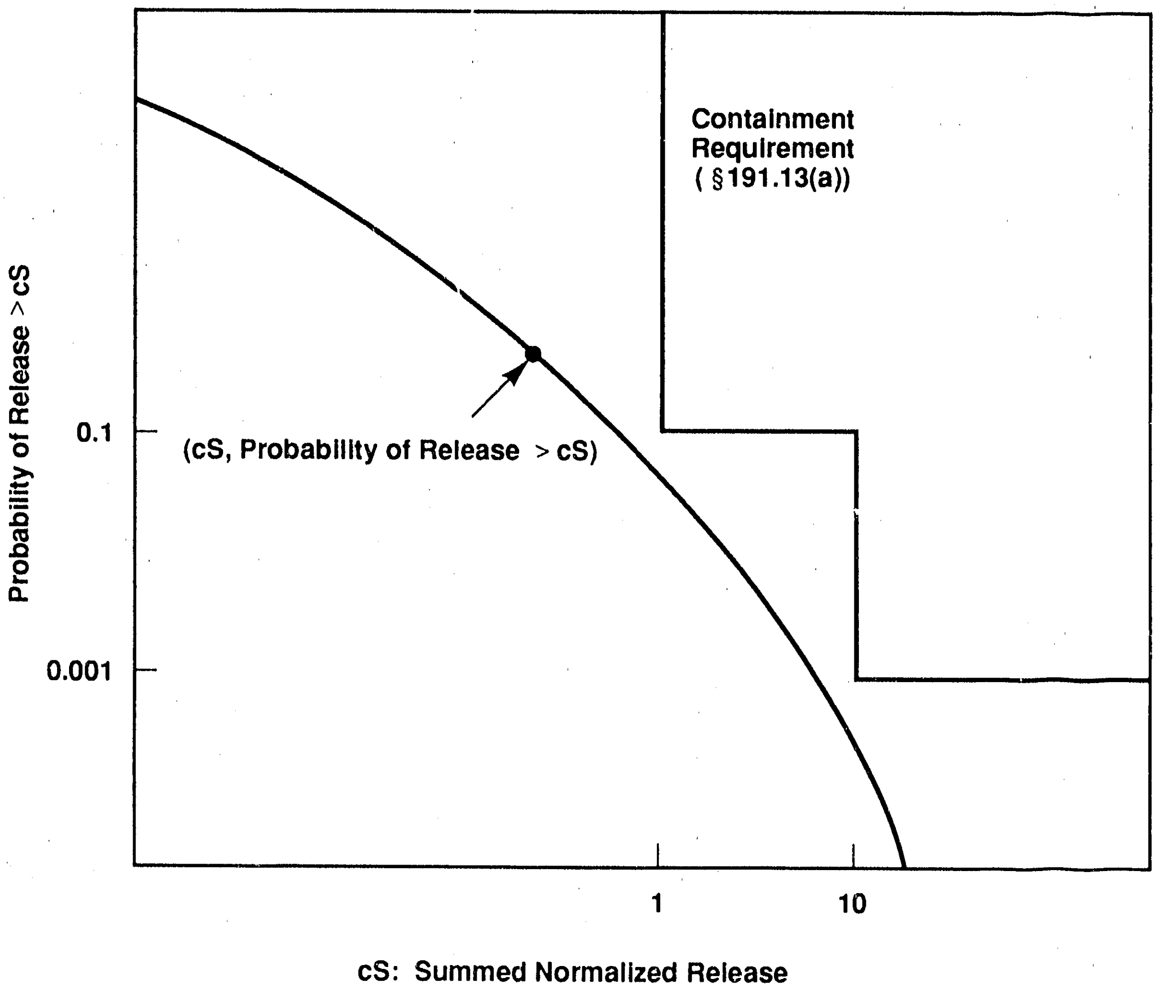

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Figure III-5. Illustration of CCDF for Summed Normalized Release for Containment Requirements (§ 191.13(a)). For a limited number of scenarios, the CCDF will look like the step functions shown in Figures III-3 and III-4.

Uncertainty in Risk

As indicated in Table II-1, a number of factors affect the uncertainty in risk results, including completeness, aggregation, model selection, imprecisely known variables and stochastic variation. The risk representation in Equation III-1 provides a convenient structure in which to discuss these uncertainties.

Completeness refers to the extent that a performance assessment includes all possible occurrences for the disposal system under consideration. In terms of the risk representation in Equation III-1, completeness deals with whether or not all possible occurrences are included in the union of the sets S_i (i.e., in $\cup_i S_i$). Aggregation refers to the division of the possible occurrences into the sets S_i and thus relates to the logic used in the construction of the sets S_i. Resolution is lost if the S_i are defined too coarsely (e.g., nS is too small) or in some other inappropriate manner. Model selection refers to the actual choice of the models for use in a risk assessment. Appropriate model choice is sometimes unclear and can affect both pS_i and $\mathbf{cS}_i$. Similarly, once the models for use have been selected, imprecisely known variables required by these models can affect both pS_i and $\mathbf{cS}_i$. Due to the complex nature of risk assessments, model selection and imprecisely known variables can also affect the definition of the S_i. Stochastic variation is represented by the probabilities pS_i, which are functions of the many factors that affect the occurrence of the individual sets S_i. The CCDFs in Figure III-3 and Figure III-4 display the effects of stochastic uncertainty. Even if the probabilities for the individual S_i were known with complete certainty, the ultimate result of a risk assessment would still be CCDFs of the form shown in Figure III-3 and Figure III-4.

The calculation of risk is driven by the sets S_i. Once these sets are determined, their probabilities pS_i and associated consequences $\mathbf{cS}_i$ must be determined. In practice, developing the S_i requires a complex and iterative process that must take into account the procedures required to determine the probabilities pS_i and the consequences $\mathbf{cS}_i$. The overall process typically is organized so that pS_i and $\mathbf{cS}_i$ will be calculated by various models whose exact configuration will depend on S_i. These models will also require a number of imprecisely known variables that could affect the definition of the S_i.

These imprecisely known variables can be represented by a vector

$$\mathbf{x} = [x_1, x_2, \ldots, x_{nV}] \quad , \tag{III-3}$$

where each x_j is imprecisely known information required in the analysis and nV is the total number of such information needs. In concept, the individual x_j could be almost anything, including externally-supplied vectors or functions required by an analysis. An overall analysis, including uncertainty and sensitivity studies, however, is most likely to be successful if the risk representation in Equation III-1 has been developed so that each x_j is a real-valued quantity for which the overall analysis requires a single value. What this value should be is not known precisely. With that idea in mind, the representation for risk in Equation III-1 can be restated as a function of $\mathbf{x}$:

$$R(\mathbf{x}) = \{(S_i(\mathbf{x}), pS_i(\mathbf{x}), \mathbf{cS}_i(\mathbf{x})), i=1, \ldots, nS(\mathbf{x})\}. \tag{III-4}$$

As $\mathbf{x}$ changes, so will $R(\mathbf{x})$ and all summary measures that can be derived from $R(\mathbf{x})$. Thus, rather than a single CCDF for each consequence value contained in **cS**, a distribution of CCDFs results from the possible values that $\mathbf{x}$ can take on.

The individual variables x_j in $\mathbf{x}$ can relate to different types of uncertainty. Individual variables might relate to completeness uncertainty (e.g., the value for a cutoff used to drop low-probability occurrences from the analysis), aggregation uncertainty (e.g., a bound on the value for nS), model uncertainty (e.g., a 0-1 variable that indicates which of two alternative models should be used), variable uncertainty (e.g., a solubility limit or a retardation for a specific isotope), or stochastic uncertainty (e.g., a variable that helps define the probabilities for the individual S_i).

Characterizing Uncertainty in Risk

If the inputs to a performance assessment, as represented by the vector $\mathbf{x}$ in Equation III-3, are uncertain, then so are the results of the assessment. Characterizing the uncertainty in the results of a performance assessment requires characterizing the uncertainty in $\mathbf{x}$. Once the uncertainty in $\mathbf{x}$ has been characterized, then Monte Carlo techniques can be used to characterize the uncertainty in the risk results.

The outcome of characterizing the uncertainty in $\mathbf{x}$ is a sequence of distributions

$$D_1, D_2, \ldots, D_{nV}, \qquad \text{(III-5)}$$

where D_j is the distribution developed for the variable x_j, $j=1, 2, \ldots, nV$, contained in $\mathbf{x}$. The definition of these distributions also might be accompanied by specifying correlations and various restrictions that further define the possible relations among the x_j. These distributions and other restrictions probabilistically characterize where the appropriate input to use in the risk assessment might fall given that the analysis is structured so that only one value can be used for each variable under consideration. In most cases, each D_j will be a subjective distribution that is developed through an expert-review process and serves to assemble information from many sources into a form appropriate for an integrated analysis. For some variables, however, the D_j may be obtained by classical statistical techniques.

Once the distributions in Equation III-5 have been developed, Monte Carlo techniques can determine the uncertainty in $R(\mathbf{x})$ from the uncertainty in $\mathbf{x}$. First, a sample

$$\mathbf{x}_k = [x_{k1}, x_{k2}, \ldots, x_{k,nV}],\ k=1, \ldots, nK, \qquad \text{(III-6)}$$

is generated according to the specified distributions and restrictions, where nK is the size of the sample. The performance assessment is then performed for each sample element $\mathbf{x}_k$, which yields a sequence of risk results of the form

$$R(\mathbf{x}_k) = \{(S_i(\mathbf{x}_k),\ pS_i(\mathbf{x}_k),\ \mathbf{c}S_i(\mathbf{x}_k)),\ i=1 \ldots, nS(\mathbf{x}_k)\} \qquad \text{(III-7)}$$

for $k=1, \ldots, nK$. Each set $R(\mathbf{x}_k)$ is the result of one complete risk assessment performed with a set of inputs (i.e., $\mathbf{x}_k$) that the review process producing the distributions in Equation III-5 concluded was possible. Further, associated with each risk result in Equation III-7 is a probability[1] or weight that can be used in making probabilistic statements about the distribution of $R(\mathbf{x})$.

---

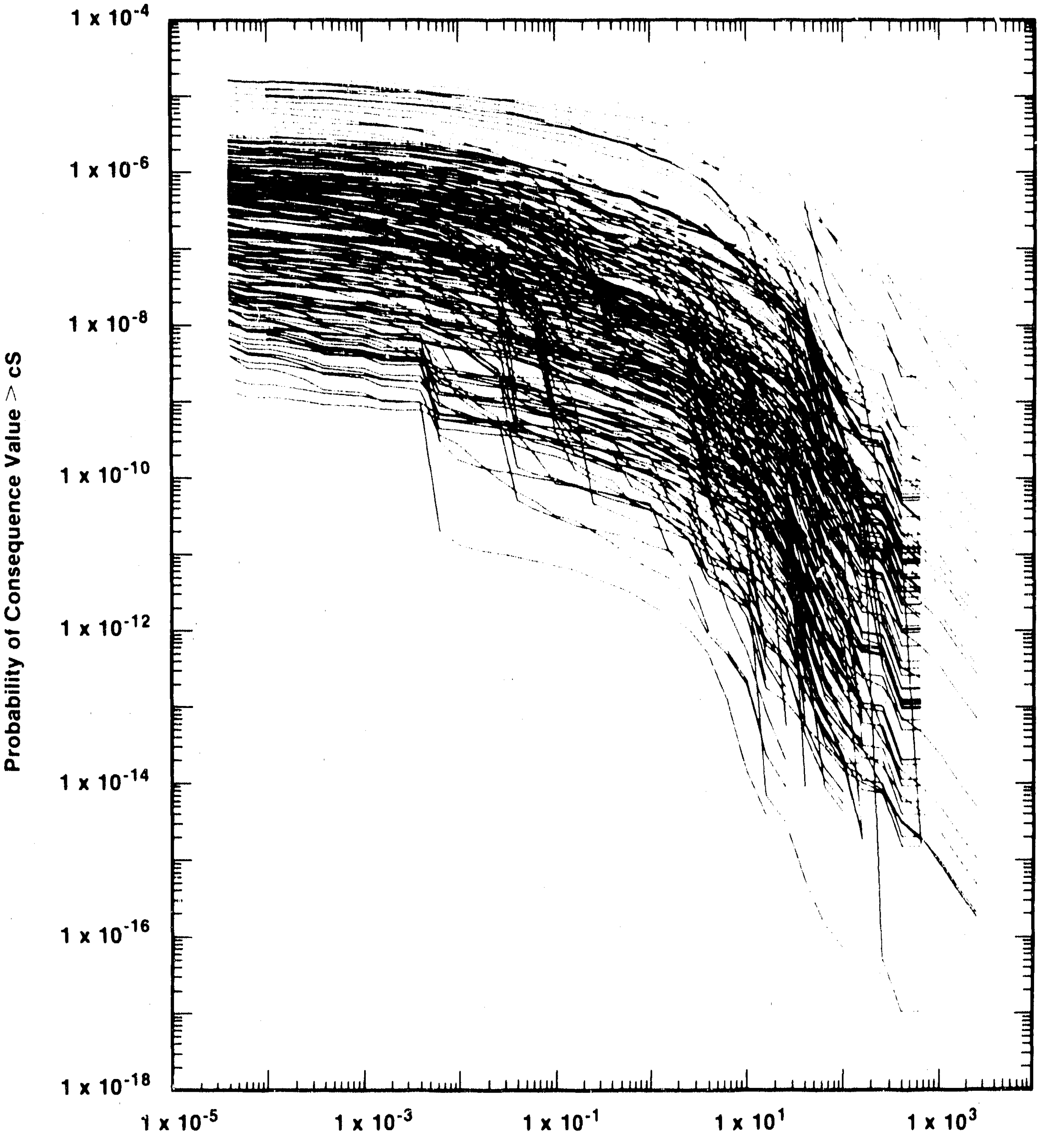
[1] In random or Latin hypercube sampling, this weight is the reciprocal of the sample size (i.e, 1/nK) and can be used in estimating means, cumulative distribution functions, and other statistical properties. Although this weight is referred to as the probability of the observation, if continuous distributions are involved, the actual probability of each observation is zero.

In most risk studies, CCDFs are the risk results of greatest interest. For a particular consequence result, a CCDF will be produced for each set $R(\mathbf{x}_k)$ of risk results shown in Equation III-7. This yields a distribution of CCDFs of the form shown in Figure III-6.

Although Figure III-6 provides a complete summary of the distribution of CCDFs obtained for a particular consequence result by propagating the sample shown in Equation III-6 through a risk assessment, the figure is rather hard to read. A less crowded summary can be obtained by plotting the mean value and selected percentile values for each consequence value on the abscissa. For example, the mean plus the 5th, 50th (i.e., median) and 95th percentile values might be used. The mean and percentile values can be obtained from the exceedance probabilities associated with the individual consequence values and the weights or "probabilities" associated with the individual sample elements. If the mean and percentile values associated with individual consequence values are connected, a summary plot of the form shown in Figure III-7 is obtained.

Figure III-6 displays the uncertainty in CCDFs that results from imprecisely known variables required in a performance assessment. Sensitivity analysis can be used to determine the importance of individual variables in giving rise to this uncertainty. One possibility is to perform an analysis for the exceedance probabilities associated with individual consequence values on the abscissa in Figure III-6. For example, standardized regression coefficients or partial correlation coefficients might be used to determine the importance of individual variables with respect to the exceedance probabilities for individual consequence values. The values of these coefficients could then be plotted above the corresponding consequence values. Figure III-8 provides an example of the results of such an analysis. As shown in this figure, variables 1, 3 and 5 are important with respect to the exceedance probabilities for smaller values of the consequence and then decrease in importance for larger consequence values. The opposite pattern of behavior is shown by variables 2 and 4.

The question is often asked: "What is the uncertainty in the results of this performance assessment?" The answer depends on exactly what result of the performance assessment is of concern. In particular, the question is often directed at either (1) the total range of risk outcomes that results from imprecisely known inputs required in the assessment or (2) the uncertainty in quantities that are derived from averaging over the outcomes derived from these inputs.



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3 Figure III-6. Example Distribution of CCDFs Obtained by Sampling Imprecisely Known Variables (after
4 Breeding, et al., 1990).

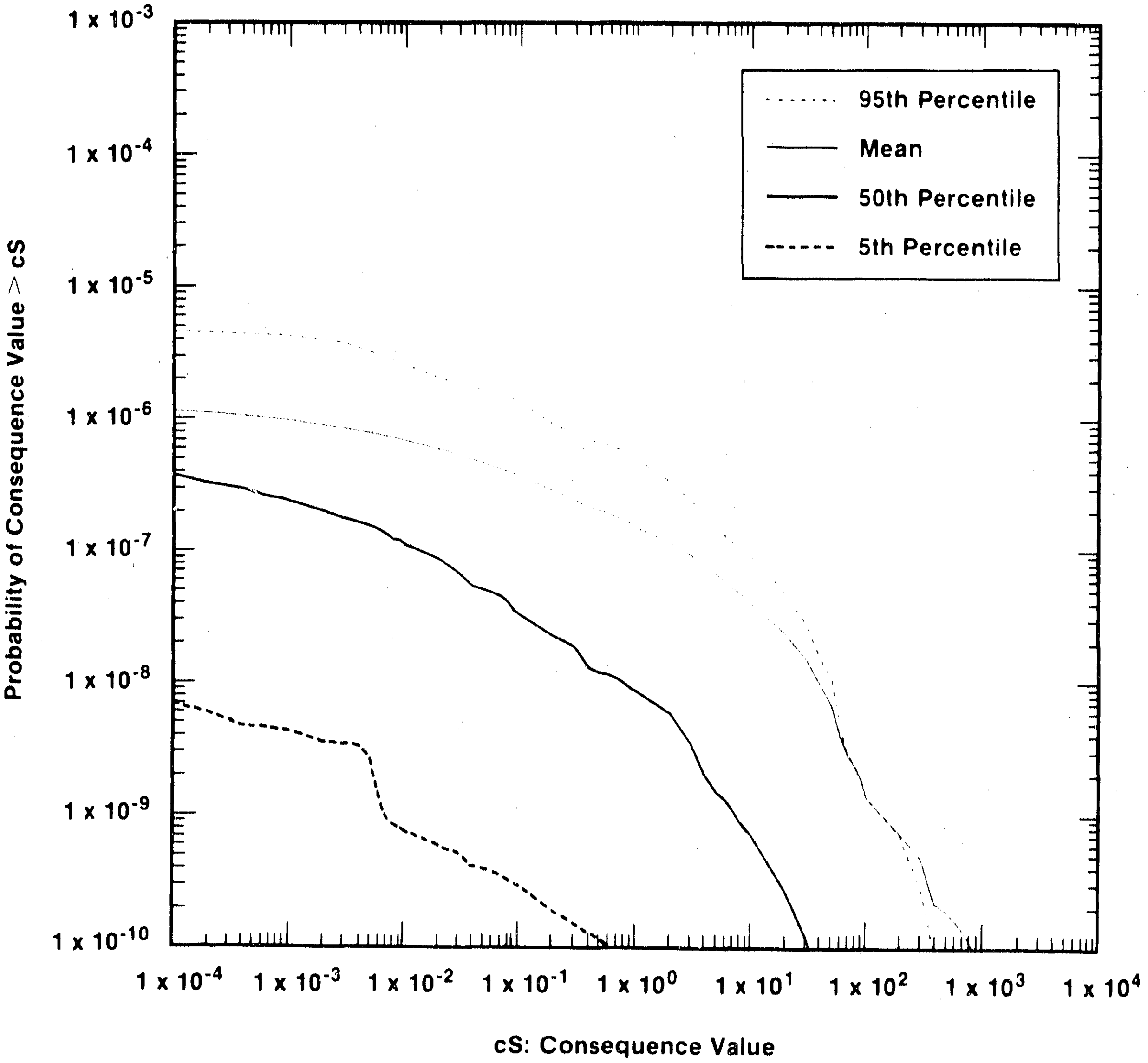

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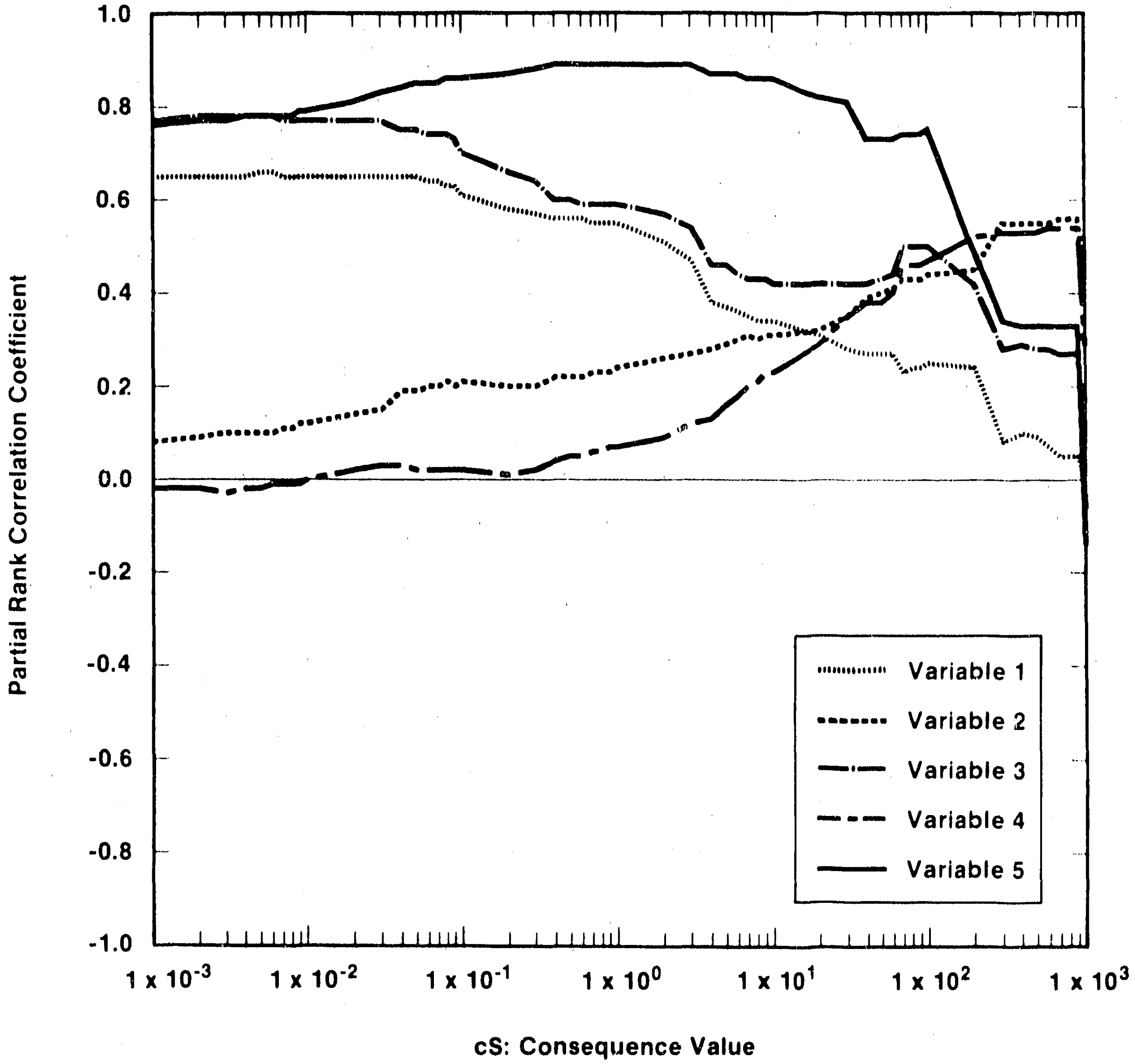
Figure III-7. Example Summary Curves Derived from an Estimated Distribution of CCDFs (after Breeding et al., 1990). The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure III-6.



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3 Figure III-8. Example Sensitivity Analysis for the CCDFs in Figure III-6 (after Breeding et al., 1990).

The answer to questions of the first type is provided by results of the form shown in Figure III-6, which displays an estimated distribution for CCDFs conditional on the distributions and models being used in the analysis. The mean and percentile curves in Figure III-7 summarize the distribution in Figure III-6. The percentile curves in Figure III-7 also provide a way to place confidence limits on the risk results in Figure III-6. For example, the probability is 0.9 that an exceedance probability falls between the 5th and 95th percentile values. However, this result is approximate since the percentile values are estimates derived from the sampling procedures and are conditional on the assumed input distributions.

Questions of the second type relate to the uncertainty in estimated means. If a distribution of CCDFs is under consideration, then the "mean" is a mean CCDF of the type shown in Figure III-7. Because most real-world analyses are very complex, assigning confidence intervals to estimated means by traditional parametric procedures is typically not possible. Replicating the analysis with independently generated samples and then estimating confidence intervals for means from the results of these replications is possible. When three or more replications are used, the t-test (Iman and Conover, 1983) can be used to assign confidence intervals with a procedure suggested by Iman (1981). When only two replications are used, the closeness of the estimated means and possibly other population parameters can indicate the confidence that can be placed in the estimates for these quantities. The results of a comparison of this latter type for the curves in Figure III-7 are shown in Figure III-9.

As indicated in the preceding discussion, there are two types of uncertainty: variation in risk results due to imprecisely known variables and variation in estimates for means and other statistical summaries that result from imprecisely known variables. Both types of uncertainty can be displayed in a single plot as shown in Figure III-10. For figures of this type, the confidence interval for the family of CCDFs would probably be obtained by a sampling-based approach as illustrated in conjunction with Figure III-7. Similarly, the mean curve would be obtained by averaging over the same curves that, because of population variability, gave rise to the confidence intervals. The confidence intervals for the mean would have to be derived by replicated sampling or some other appropriate statistical procedure.

Risk and the EPA Limits

With respect to the EPA Containment Requirements (§ 191.13(a)), the sets S_i, $i = 1, \ldots, nS$ appearing in Equation III-1 are simply the scenarios selected for consideration. Ultimately, these scenarios derive from the significant "processes" and "events" referred to in the Standard. These scenarios will

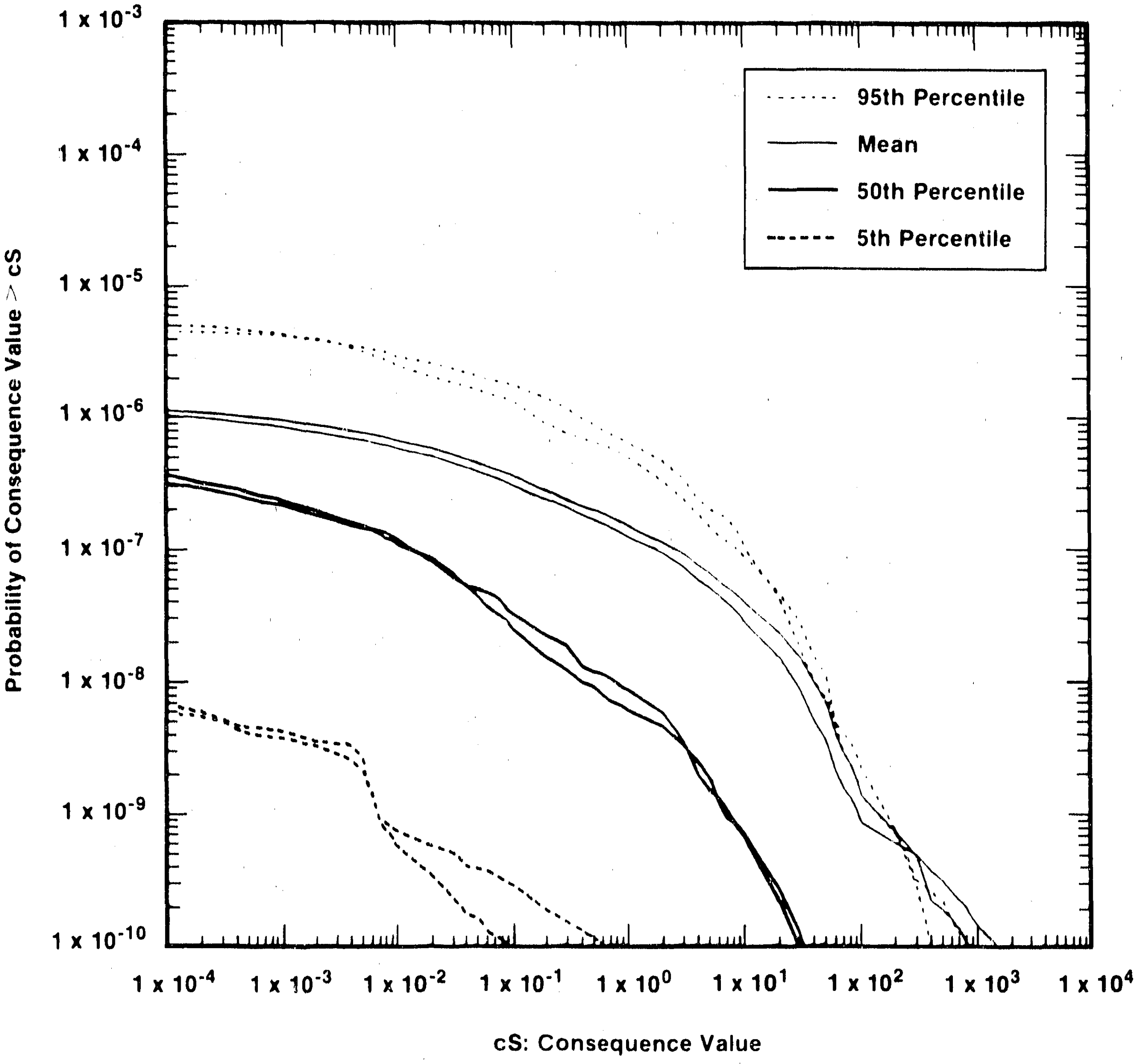

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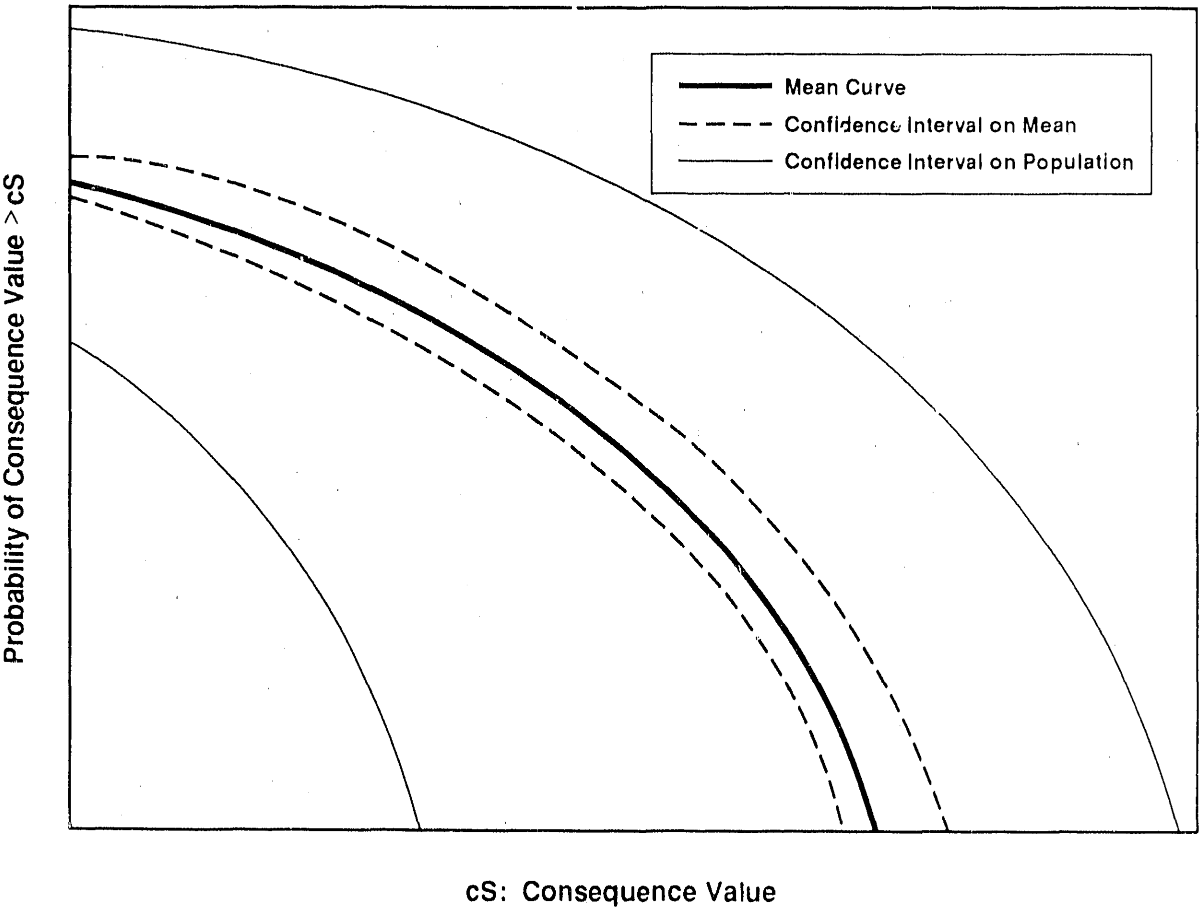
Figure III-9. Example of Mean and Percentile Curves Obtained with Two Independently Generated Samples for the Results Shown in Figure III-6 (after Breeding et al., 1990; additional discussion is provided in Iman and Helton, in prep.).



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3 Figure III-10. Example Confidence Bands for CCDFs (Helton, 1990).

always be sets of similar occurrences because any process or event when examined carefully will have many variations. The pS_i are the probabilities for the S_i. Thus, each pS_i is the total probability for all occurrences contained in S_i. Finally, $\mathbf{cS}_i$ is a vector of consequences associated with S_i. Thus, $\mathbf{cS}_i$ is likely to contain the releases to the accessible environment for the individual radionuclides under consideration as well as the associated normalized release. In practice, the total amount of information contained in $\mathbf{cS}_i$ is likely to be quite large.

The risk representation in Equation III-1 can be illustrated with the preliminary performance assessment presented in this report. This assessment identifies eight scenarios (i.e., $nS = 8$) for consideration (see Chapter IV). The logic leading to these scenarios and two calculations of their probabilities (i.e., pS_i) are illustrated in Figures IV-10 and IV-11. The sets S_i appearing in Equation III-1 are defined by the correspondences

$$S_1 \sim \text{Base Case},\ S_2 \sim \text{E2},\ S_3 \sim \text{E1},\ S_4 \sim \text{E1E2},$$
$$S_5 \sim \text{TS},\ S_6 \sim \text{TSE2},\ S_7 \sim \text{TSE1},\ S_8 \sim \text{TSE1E2}.$$

Two different formulations for the pS_i are given in these figures. A complex sequence of linked computer programs calculated the consequences associated with the vectors $\mathbf{cS}_i$.

If the probabilities pS_i and consequences $\mathbf{cS}_i$ associated with the S_i were known with certainty, then a single CCDF of the form shown in Figure III-3 could be constructed for comparison with the EPA release limits. Unfortunately, neither the pS_i nor the $\mathbf{cS}_i$ are known with certainty. When this fact is incorporated into the representation in Equation III-1, the set R can be expressed as

$$R(\mathbf{x}) = \{(S_i,\ pS_i(\mathbf{x}),\ \mathbf{cS}_i(\mathbf{x}),\ i = 1, \ldots, nS = 8\}, \qquad \text{(III-8)}$$

where $\mathbf{x}$ represents a vector of imprecisely known variables required in the estimation of the pS_i and the $\mathbf{cS}_i$. For the preliminary analyses presented here, $\mathbf{x}$ consists of the 29 variables in Table C-2 (Appendix C) plus the values for the probabilities of the individual scenarios. For the purpose of this example, the variables in $\mathbf{x}$ that correspond to the pS_i are assumed to be uniformly distributed between the scenario probabilities given in Figures IV-10 and IV-11.

The effect of uncertainties in **x** was investigated by generating a Latin hypercube sample (McKay et al., 1979) of size 40 from the variables contained in **x**. This creates a sequence of sets $R(\mathbf{x})$ of the form

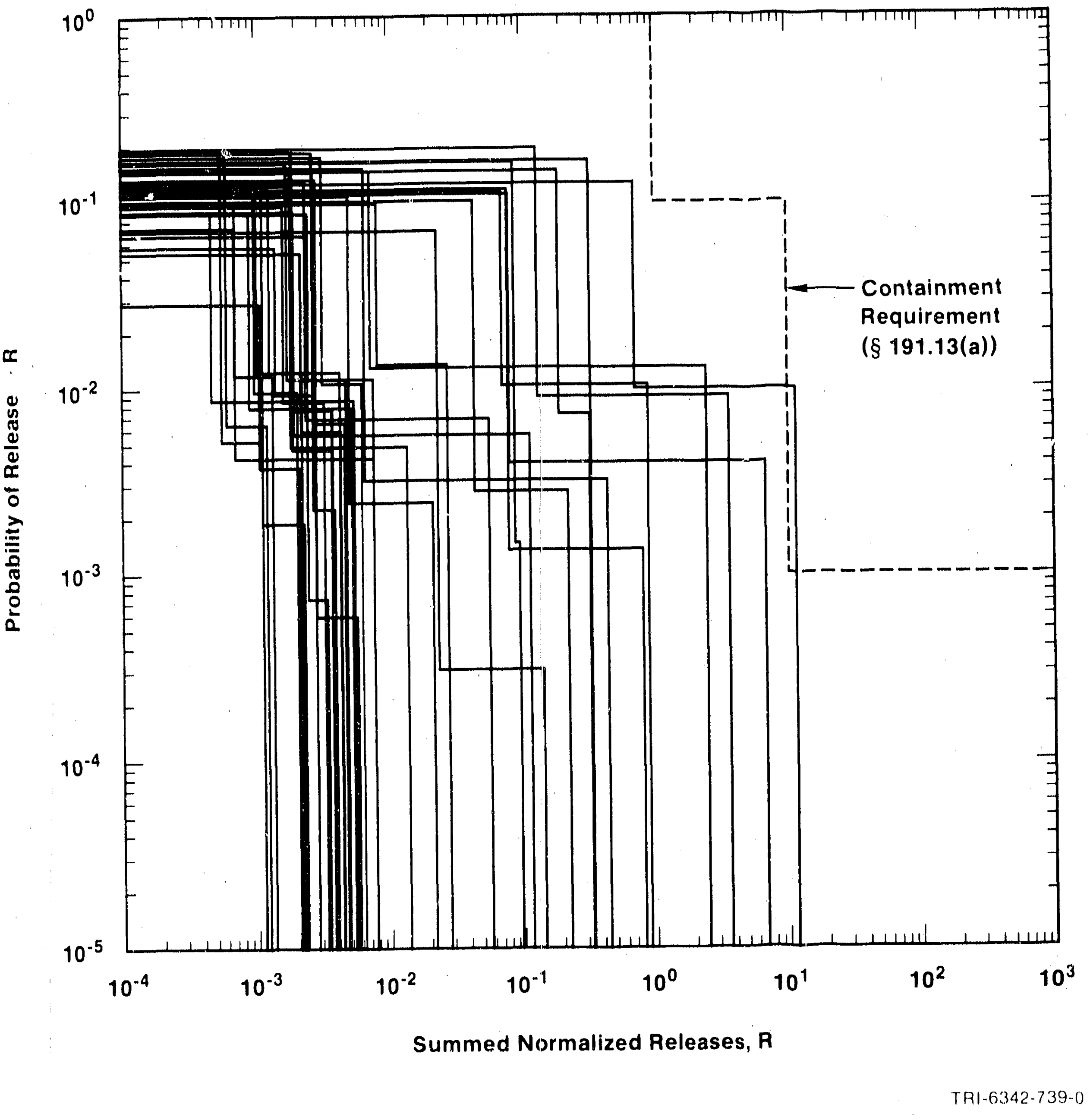
$$R(\mathbf{x}_k) = \{(S_i, pS_i(\mathbf{x}_k), \mathbf{cS}_i(\mathbf{x}_k)), i = 1, \ldots, nS = 8\} \qquad \text{(III-9)}$$

for k = 1, ..., 40, where $\mathbf{x}_k$ is the value for **x** in sample element k. Actually, no calculations were performed in this preliminary analysis for the scenarios involving subsidence. For this example analysis, the releases associated with the subsidence scenarios were assumed to be the same as the corresponding scenarios for the nonsubsidence case (i.e., $\mathbf{cS}_{i+4}(\mathbf{x}_k) = \mathbf{cS}_i(\mathbf{x}_k)$ for i = 1,2,3,4).

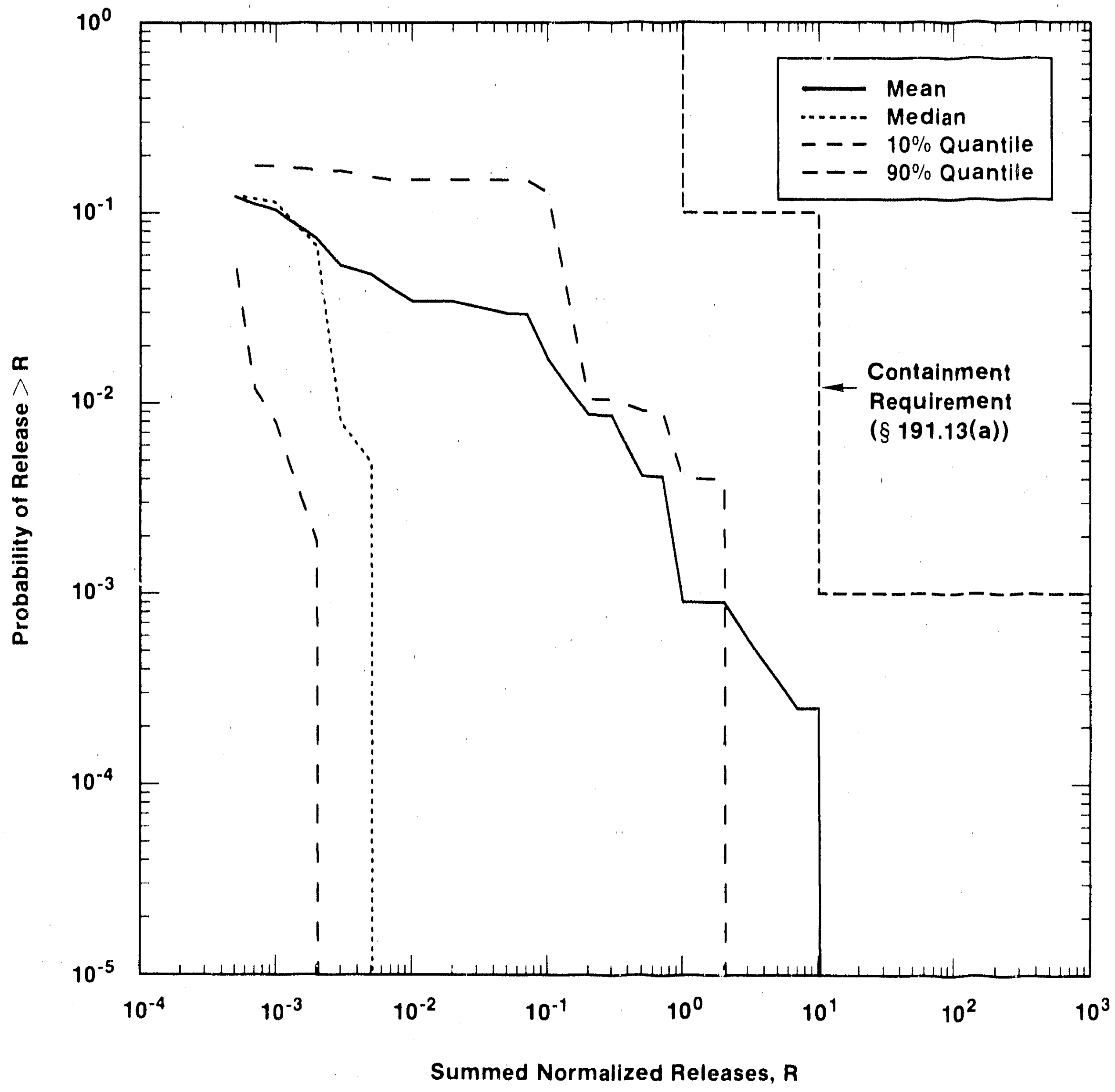
As previously illustrated in Figure III-3, a CCDF can be constructed for each sample element and each consequence measure contained in **cS**. Figure III-11 shows an example distribution of CCDFs for the normalized EPA release, calculated for illustrative purposes only using preliminary WIPP models and data. Each curve in this figure is a CCDF that would be the appropriate choice for comparison against the EPA requirements <u>if</u> $\mathbf{x}_k$ contained the correct variable values for use in determining the pS_i and $\mathbf{cS}_i$. The distribution of CCDFs in Figure III-11 reflects the distributions assigned to the sampled variables in **x**. Actually, what is shown is an approximation to the true distribution of CCDFs, conditional on the assumptions of this analysis. This approximation was obtained with a Latin hypercube sample of size 40. In general, a larger sample would produce a better approximation but would not alter the fact that the distribution of CCDFs was conditional on the assumptions of the analysis.

The individual CCDFs in Figure III-11 have a very simple structure because only scenarios E1, E2 and E1E2 have nonzero releases. Further, the releases for E1 and E2 are the same (see "Panel Program (PANEL)" in Chapter V). As a result, each CCDF has only three steps associated with it. Considering more scenarios with nonzero releases would lead to more complex curves.

Figure III-11 is rather cluttered and hard to read. As discussed in conjunction with Figure III-7, mean and percentile curves can be used to summarize the family of CCDFs in Figure III-11. The outcome of this construction is shown in Figure III-12, which shows the resultant mean curve and 90th, 50th (median) and 10th percentile curves. The mean curve has generally been proposed for showing compliance with § 191.13(a). This usage is consistent with the SNL interpretation of the Standard, and the mean curve will be the primary summary measure in the performance assessments for the WIPP.



3 Figure III-11. Example Distribution of CCDFs Generated by Latin Hypercube Sampling for Comparison
4 with the Containment Requirements (§ 191.13(a)).



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3 Figure III-12. Mean and Percentile Curves for the Example Family of CCDFs Shown in Figure III-11.

Now that Figures III-11 and III-12 have been introduced, the nature of the EPA's probability limits can be elaborated. Specifically, § 191.13(a) requires that the probability of exceeding a summed normalized release of 1 shall be less than 0.1 and that the probability of exceeding a summed normalized release of 10 shall be less than 0.001. Because quantities required in a performance assessment are imprecisely known, these probabilities can never be known with certainty. By placing distributions on imprecisely known quantities, however, distributions for these probabilities can ultimately be obtained. To the extent that the distributions assumed for the original variables are subjective, so also will be the distributions for these probabilities.

In our example, the distribution of probabilities at which a normalized release of one will be exceeded can be obtained by drawing a vertical line through 1 on the abscissa in Figure III-11. This line will cross the 40 CCDFs generated in this example to yield a distribution of 40 exceedance probabilities. By this point on the abscissa, 36 of the CCDFs have already dropped to zero. Thus, the resulting distribution will contain 36 zeros and 4 nonzero values. A similar construction can be performed for a normalized release of 10. In this case, a distribution containing 39 zeros and 1 nonzero value is obtained. Means (actually, estimates for the expected value of the true distribution, conditional on the assumptions of this analysis) for these two distributions can be obtained by summing the 40 observed values and then dividing by 40. The result of this calculation at 1, 10, and other points on the abscissa appears as the mean curve in Figure III-12.

The EPA assumes in the guidance in Appendix B that, whenever practicable, the results of a performance assessment should be assembled into a CCDF. This is entirely consistent with the representation of risk given in Equation III-1. The EPA further assumes that, when uncertainties in parameters are considered, the effects of these uncertainties can be incorporated into a single CCDF. Calculating a mean CCDF as shown in Figure III-12 is one way to obtain a single CCDF. However, there are other ways in which a single CCDF can be obtained. For example, a median or 90th percentile curve as shown in Figure III-12 could be used. Whenever 40 (many) curves are reduced to a single curve, however, information on uncertainty is lost.

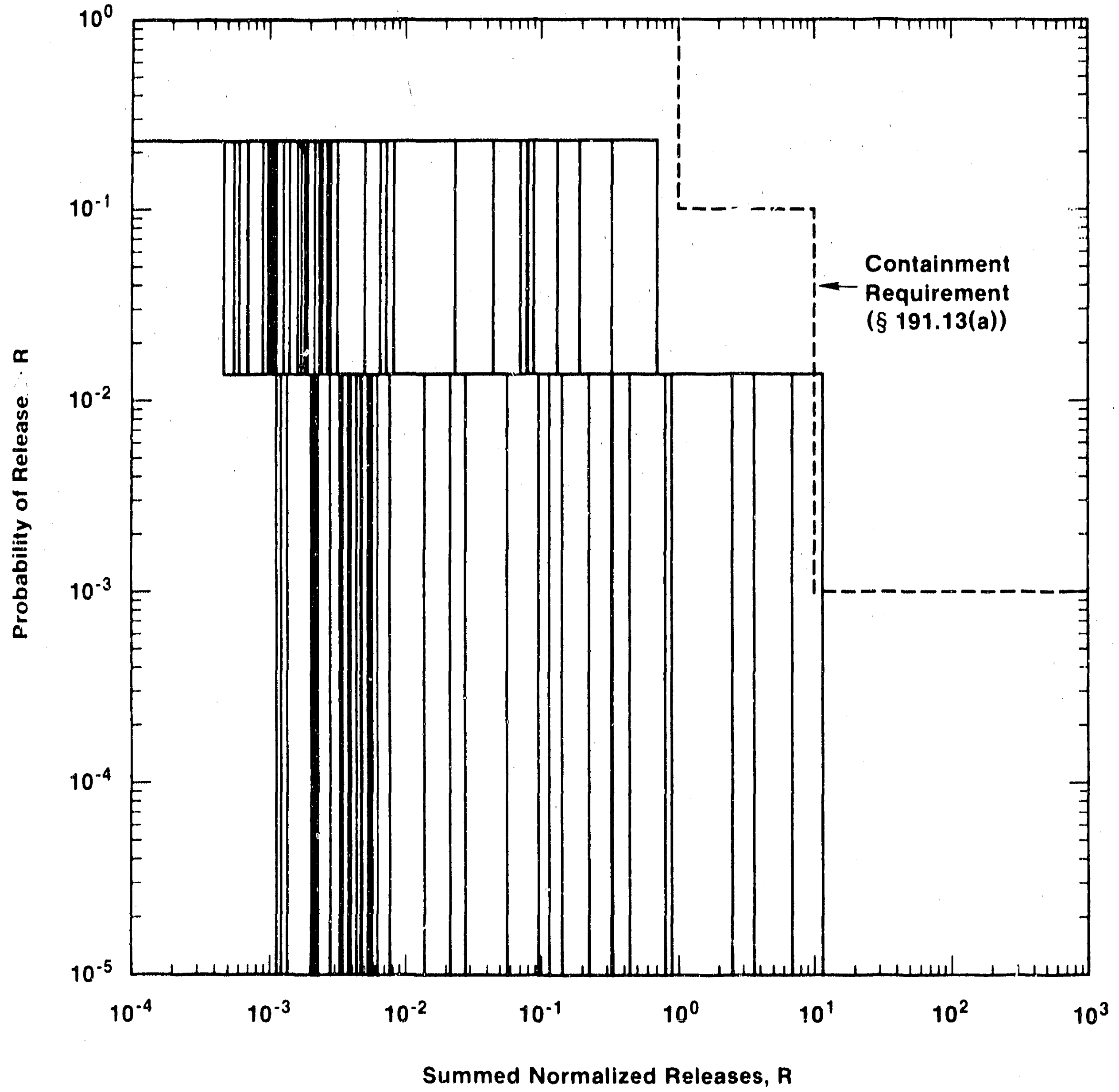
Replicated sampling can characterize the uncertainty in an estimated mean CCDF or other summary curve. Incorporating the uncertainty into the estimated value in this way is quite different from displaying the variability or uncertainty in the population from which the estimate is derived (Figure III-10). For example, the uncertainty on the estimated mean curve in Figure III-12 is probably far less than the variability in the population of CCDFs that was averaged to obtain this mean.

Preliminary analyses for § 191.13(a) have typically assumed that the individual scenario probabilities are known with certainty and that the only uncertainties in the analysis relate to the manner in which the summed normalized release required for comparison with the EPA Standard is calculated. As an example, Figure III-13 shows the family of CCDFs that results when the same sample used to construct the CCDFs in Figure III-11 is used but the individual scenario probabilities are fixed at the values shown in Figure IV-9. In this case, the values for the pS_i do not change from sample element to sample element, but the values for $\mathbf{cS}_i$ do. This results in a very simple structure for the CCDFs in which the step heights for all CCDFs are the same. Mean and percentile curves can be constructed from these CCDFs as before and are shown in Figure III-14.

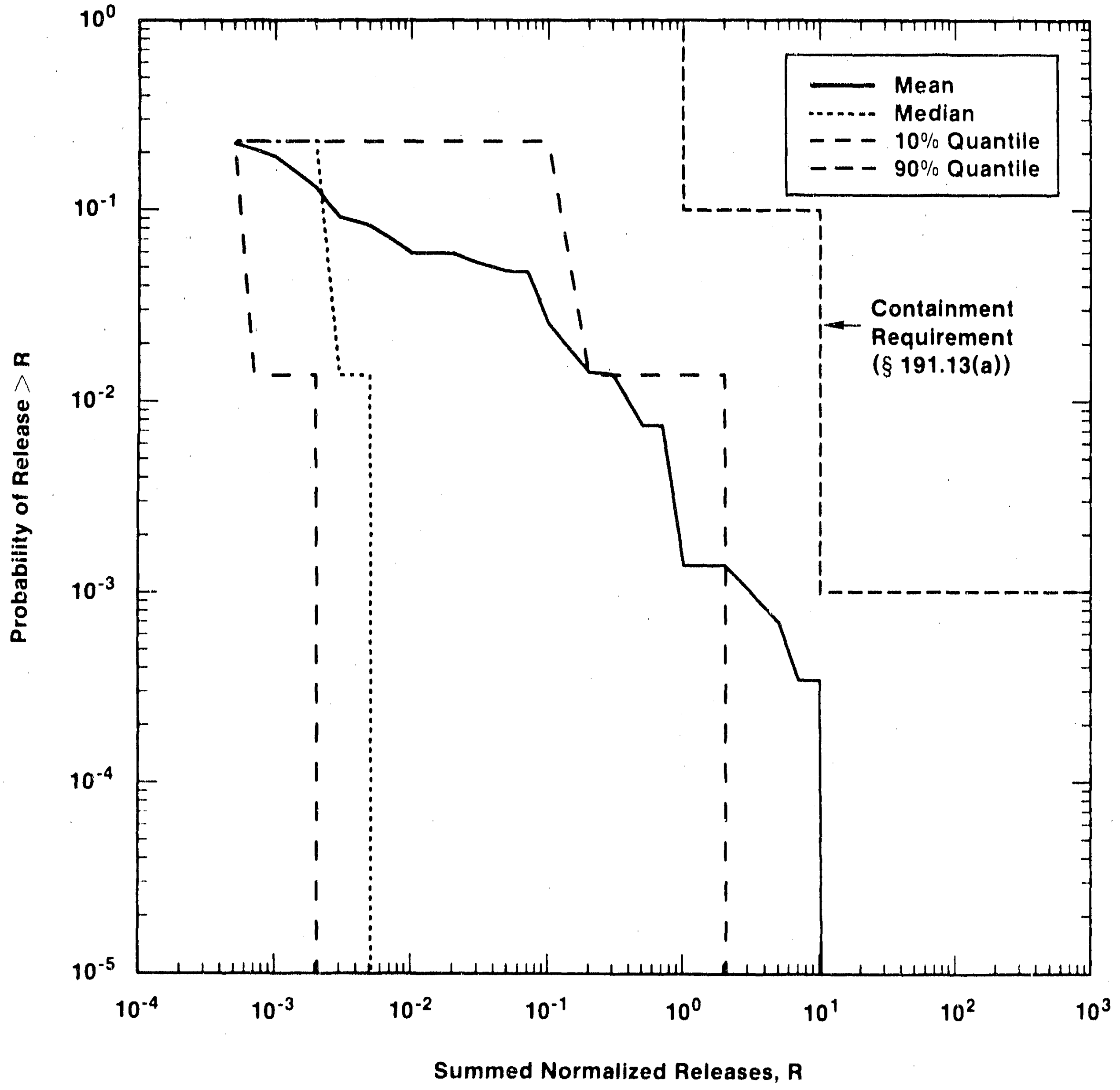
Another approach to constructing a CCDF for comparison with the EPA Standard is based on initially constructing a conditional CCDF for each scenario and then vertically averaging these conditional CCDFs with the probabilities of the individual scenarios as weights. This approach is described in Cranwell et al. (1987; also see Cranwell et al., 1990; Hunter et al., 1986) and has been extensively used in calculating CCDFs for comparison with § 191.13(a). Figure III-15 gives a schematic representation for this construction approach. This approach is applicable to situations in which the scenario probabilities are fixed, and in this case, yields the same mean CCDF as shown in Figure III-14.

MONTE CARLO TECHNIQUES

One informal and four formal techniques are available for performing uncertainty and sensitivity analyses for complex models. The informal technique involves changing a single model assumption, or sometimes a group of related assumptions, and observing the resultant changes in model predictions. This is sometimes called the *ceteris paribus* approach and has been widely used in sensitivity studies for the WIPP. The *ceteris paribus* approach has the advantage of allowing complete control over the changed assumption, without ambiguity in the source of any alterations in a model's predictions. This approach, however, can be very inefficient computationally when many modeling assumptions must be investigated. This approach provides no insight into the distributions of model predictions that result from distributions assigned to model inputs.



3 Figure III-13. Example Family of CCDFs Generated by Latin Hypercube Sampling for Comparison with
4 the Containment Requirements in Which the Scenario Probabilities are the Same for All
5 Sample Elements.



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3 Figure III-14. Mean and Percentile Curves for the Example Family of CCDFs Shown in Figure III-13.

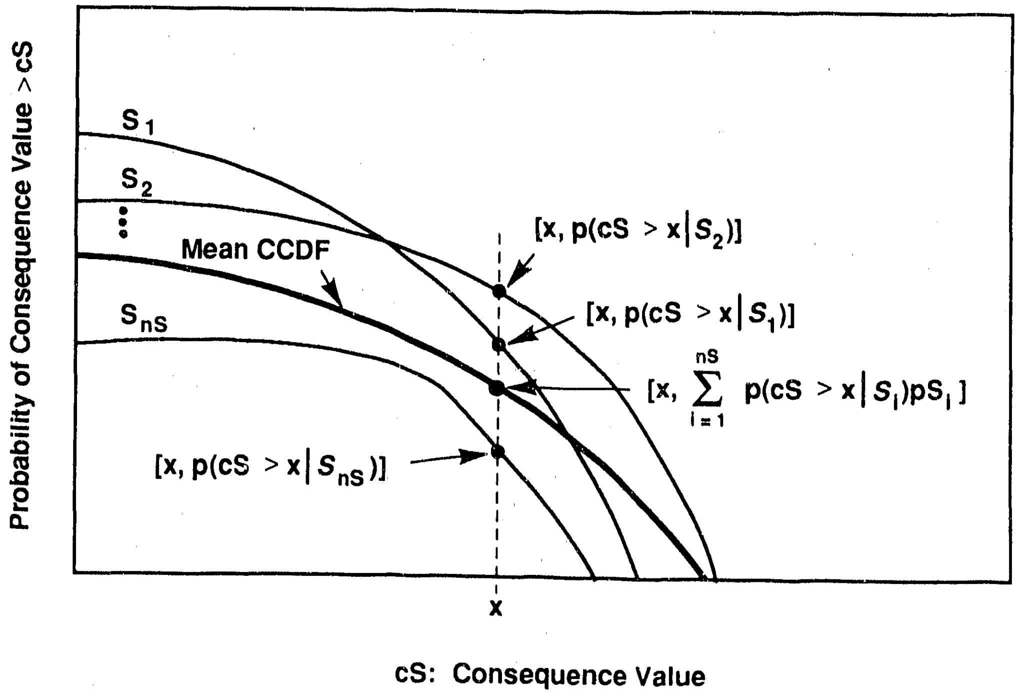

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Figure III-15. Construction of Mean CCDF from Conditional CCDFs. $p(cS>x \mid S_i)$ is the probability of a normalized release exceeding x over 10,000 years given that scenario S_i has occurred. The ordinate displays conditional probability for the CCDFs for the individual events S_i and probability for the mean CCDF. When the probabilities pS_i are small, the mean CCDF may fall far below most of the individual conditional CCDFs (Helton, 1990).

Formal techniques for uncertainty and sensitivity analyses provide a more systematic way to determine the impacts of assumptions on results. Four techniques have been widely used: differential analysis, Monte Carlo analysis, response surface methodology, and Fourier amplitude sensitivity test. These techniques are compared elsewhere (Helton, 1990; Iman and Helton, 1985).

The WIPP performance assessment has selected Monte Carlo analysis as the primary approach for performing formal uncertainty and sensitivity analyses. A Monte Carlo analysis is based on performing multiple model evaluations with probabilistically selected model input, and then using the results of these evaluations to determine both the uncertainty in model predictions and the input variables that give rise to this uncertainty. As discussed in Helton (1990), a Monte Carlo analysis involves five steps.

First, a range and distribution are selected for each x_j. These selections will be used in the next step to generate a sample from the x_j. If the analysis is primarily exploratory, then rather crude (e.g., uniform and loguniform) distributions may be assumed; however, if precise uncertainty results are desired for y, then corresponding care must be used in specifying the distributions for the x_j. Procedures for developing variable distributions for use in the WIPP performance assessment are discussed in Tierney (1990) and Helton (1990). Typically these distributions characterize where the value for a fixed, but imprecisely known, model parameter is likely to be located.

Second, a sample is generated from the ranges and distributions specified in the first step. This step produces a sequence of sample elements of the form

$$\mathbf{x}_k = [x_{i1}, x_{i2}, \ldots, x_{i,nV}], \; k = 1, 2, \ldots, nK, \qquad \text{(III-10)}$$

where nV is the number of independent (i.e., sampled) variables and nK is the sample size. The most widely used sampling techniques are random sampling, importance sampling, and Latin hypercube sampling (McKay et al., 1979). The WIPP performance assessment will use Latin hypercube sampling because it efficiently stratifies the range of each sampled variable (Helton, 1990).

Third, the model is evaluated for each sample element shown in Equation III-10, creating a sequence of results of the form

$$y_k = f(x_{k1}, x_{k2}, \ldots, x_{k,nV}) = f(\mathbf{x}_k), \; k = 1, 2, \ldots, nK, \qquad \text{(III-11)}$$

where the function f represents the model under consideration. In essence, the function f maps the analysis inputs (i.e., the $\mathbf{x}_k$) to the analysis results (i.e., the $\mathbf{y}_k$), and the mapping can be studied in subsequent uncertainty and sensitivity analyses. The CAMCON system has been developed as part of the WIPP performance assessment to facilitate both the performance and archival storage of the model evaluations associated with this step (Rechard, 1989; Rechard et al., 1989; Rechard et al., 1990c). Additional discussion of CAMCON is given in Chapter V.

Fourth, the results shown in Equation III-11 become the basis for an uncertainty analysis. One way to characterize the uncertainty in y is with a mean value and a variance. When either random sampling or Latin hypercube sampling is used to generate the sample shown in Equation III-10, the expected value and variance for y can be estimated by

$$E(y) \doteq \sum_{k=1}^{nK} y_k/n \tag{III-12}$$

and

$$V(y) \doteq \sum_{k=1}^{nK} \left[y_k - E(y)\right]^2/(nK-1), \tag{III-13}$$

respectively. The averaging process shown in Equation III-12 is conceptually the same as the averaging process used to produce the mean CCDF shown in Figure III-7. Characterizing uncertainty with expected value and variance reduces to two numbers all of the information in Equation III-11 about the variability in y. Clearly, information is lost in this process. Another way to summarize the variability in y is through an estimated distribution function. In particular, this function is given by the step function defined by the points

$$(y_k, k/nK), \ k = 1, 2, \ldots, nK, \tag{III-14}$$

where the y_i are assumed to be ordered so that $y_k \le y_{k+1}$. The step function can be plotted to display all the information contained in Equation III-11 about the uncertainty in y. A very important aspect of the uncertainty studies that can be performed as part of a Monte Carlo analysis is that a surrogate or intermediate model is not necessary to obtain the results in Equations III-12, III-13 and III-14. In contrast, both differential analysis and response surface methodology require an intermediate model before uncertainty analysis can be performed.

The final step is sensitivity analysis that explores the mapping from analysis input to analysis results is defined by the relationship in Equation III-11. Many techniques are available for this exploration. One of the simplest but also most useful is scatterplots. A scatterplot for independent variable x_j and the dependent variable y is a plot of the points

$$(x_{kj}, y_k), \quad k = 1, 2 \ldots, nK. \qquad \text{(III-15)}$$

Such plots often reveal thresholds or nonlinearities in the relationship between x_j and y. Another useful procedure is stepwise regression analysis. In this procedure, a regression model relating the x_j to y is constructed by bringing in one variable at a time. The importance of each variable is the order in which variables enter the model, the size and sign of the standardized regression coefficients, and the changes in R^2 values as additional variables enter the model. The R^2 value, also called the coefficient of determination, is the fraction of the total variability in the dependent variable that can be accounted for by the regression model. Often, model predictions are not single-valued as shown in Equation III-11; rather, many values are produced because of temporal or spatial variation. When this is the case, plots of standardized regression coefficients or partial correlation coefficients as functions of time or location may be revealing.

Additional information on Monte Carlo analysis is available elsewhere (Zimmerman et al., 1990; Helton et al., 1985; Gardner and O'Neill, 1983; Iman and Conover, 1982a; Iman and Conover, 1982b; Iman and Conover, 1980a; Iman and Conover, 1980b; Schwartz and Hoffman, 1980; McKay et al., 1979).

Monte Carlo analysis was selected as the primary approach for formal uncertainty and sensitivity analyses in the WIPP performance assessment for several reasons (Helton, 1990). Because they fully stratify the range of each variable, Monte Carlo techniques are particularly appropriate for analyses in which large uncertainties are associated with the independent variables. These techniques provide direct estimates for distribution functions. Monte Carlo techniques do not require modifying the original model or adding numerical procedures, and can be used to propagate uncertainties through a sequence of separate models. Examples of this type of analysis can be found in performance assessments for hypothetical radioactive-waste disposal sites (e.g., Bonano et al., 1989; Cranwell et al., 1987) and probabilistic risk assessments for nuclear power plants (e.g., U.S. Nuclear Regulatory Commission, 1989). Monte Carlo techniques create a mapping from analysis input to analysis results that is rich in information because of the full stratification over the range of each input variable and the wide variety of output variables that can be generated and saved. Once produced and stored, this mapping can be explored in many ways.

PERFORMANCE ASSESSMENT PROCESS

Performance assessment is a dynamic process that relies on iterative simulations using techniques and data developed as work progresses. Neither the data base nor the models are fixed at this stage, and all aspects of the compliance assessment system are subject to review as new information becomes available. Much of the modeling system described in this report will not change as the work progresses. Some of it will change, however, as problems are resolved and new models and data are incorporated into the system for use in subsequent simulations.

In some cases improvements in the modeling system will occur in part as a result of information generated by the performance assessment process. New models for specific components of the modeling system, such as the helical flow model for erosion of waste by circulating drilling fluid described in Chapter V, are introduced as they become available. Sensitivity analyses identify aspects of the modeling system where variability and uncertainty have the greatest potential to affect performance, thereby helping guide ongoing research. For example, sensitivity analyses corroborated the importance of better characterizing radionuclide solubility and waste permeability (Bertram-Howery and Swift, 1990).

In other cases, improvements in the compliance assessment system will result from developments in the Project's understanding of the disposal system. For example, preliminary results presented in Chapter VI were calculated using the initial CH-waste inventory from Lappin et al. (1989) and an RH-waste inventory available in early September, 1990. Both inventories will be updated as new information becomes available.

Sensitivity analyses are being performed for each scenario that appears to be of regulatory interest (e.g., Marietta et al., 1989; Helton, 1990). Sensitivity analysis for a scenario begins with a description of the conceptual model of the disposal system. The scenario may affect some or all of the subsystems of the conceptual model: (1) the disposal rooms that make up each panel, (2) the panel seals, (3) the access drifts, (4) the shafts and their seals, and (5) hydrogeology of the controlled area. Each subsystem is made up of components such as the stratigraphic units of the controlled area or the waste, backfill, brine, gas, and disturbed rock zone (DRZ) of the disposal room.

Sensitivity analysis can be performed on individual components, the subsystem, or the system as a whole. Sensitivity analysis of an individual component provides understanding of an individual model and the processes it represents. For example, the removal of cuttings or materials from a waste room after closure is controlled by the flow through the borehole, the shear strength of the materials in the collapsed room, and the circulation through the room. In this example, all three processes are important. In some cases, however, one or more of the processes or properties can be shown to be less important and thus require less effort to decrease the uncertainty in the range and distribution of that property to an acceptable level. For subsystem sensitivity studies of a given scenario, all the components are varied throughout their range to see if they have a large effect on the results. Again, for the scenario being addressed, some of the components will be important and others unimportant. The response of a component to all scenarios that will be included in the final performance assessment will show the importance of the component within the subsystem.

Sensitivity analysis of the whole system provides insight into the relative importance of modules and their processes within the whole system in determining the performance measure. A detailed description of the sensitivity analysis techniques being used in the WIPP performance assessment is available in Helton (1990).

Sensitivity analysis provides guidance to the Project (Bertram-Howery and Hunter, 1989a). Because new data that may change the conceptual model, or the ranges and distributions of parameters, or both, continues to become available throughout the life of the WIPP Project, sensitivity analyses must be iterative. Most of the critical data needs can be identified as those for parameters that are rapidly changing for the conditions in the scenario, those that have a broad range and poorly defined distribution, or those that are in the critical components of the system. Sensitivity analysis of the computational system for a scenario helps identify those parameters that are important in modifying the response of a model segment and those model segments that are important in modifying the response of the system. The sensitive parameters or model segments are then analyzed in more detail to see how they are changing. For those components that are changing nonlinearly, more precise values will be needed for parameter ranges and distributions (Bertram-Howery and Hunter, 1989a).

Sensitivity analysis provides a basis for decisions to upgrade or downgrade the priorities of the data collection activities. Setting priorities can improve efficiency in use of finite resources. Until all of the critical scenarios have been subjected to sensitivity analyses and the relative importance and certainty of each parameter determined for all scenarios, care must be taken not to change data priorities prematurely. If a critical parameter within a scenario, when known to the certainty achievable with current technology, could cause the scenario to violate the Standard, then the sensitivity analysis can define repository design modifications to lessen the effect of that parameter on long-term performance (Bertram-Howery and Hunter, 1989a).

Several sets of sensitivity analyses have been performed. Some focused on providing guidance to individual component studies. Some were concerned with processes within a room or panel during and after closure. That work resulted in focusing the Project toward a better understanding of both brine inflow and the source term (including gas generation and radionuclide solubilities). Other analyses demonstrated the potential importance of human-intrusion drilling processes, brine pocket penetration, and modifications to the waste form in calculating the final CCDF (e.g., Marietta et al., 1989; Rechard et al., 1990a; Bertram-Howery and Swift, 1990). Deterministic analyses (Lappin et al., 1989) demonstrated the importance of the dual porosity assumption for the Culebra aquifer in calculating the performance measure. Those analyses helped to identify a critical list of parameters for both short-term and long-term performance of the WIPP that will be addressed in performance assessment sensitivity studies.

The relationship of the research and development work on natural and engineered barrier systems to performance assessment is illustrated in Figure III-16. At this stage in the process, the compliance assessment system changes month by month. Table III-1 summarizes some significant changes made during 1990. Continuous publication of performance assessment results as each new change is made is not feasible. As will be the case in subsequent *Preliminary Comparison* reports, results presented here reflect the improvements made during the previous year. Because the process is dynamic, however, both the results and the description of the system are in part already out of date. This report presents a snapshot of a system that will continue to evolve until the final *Comparison* is complete.

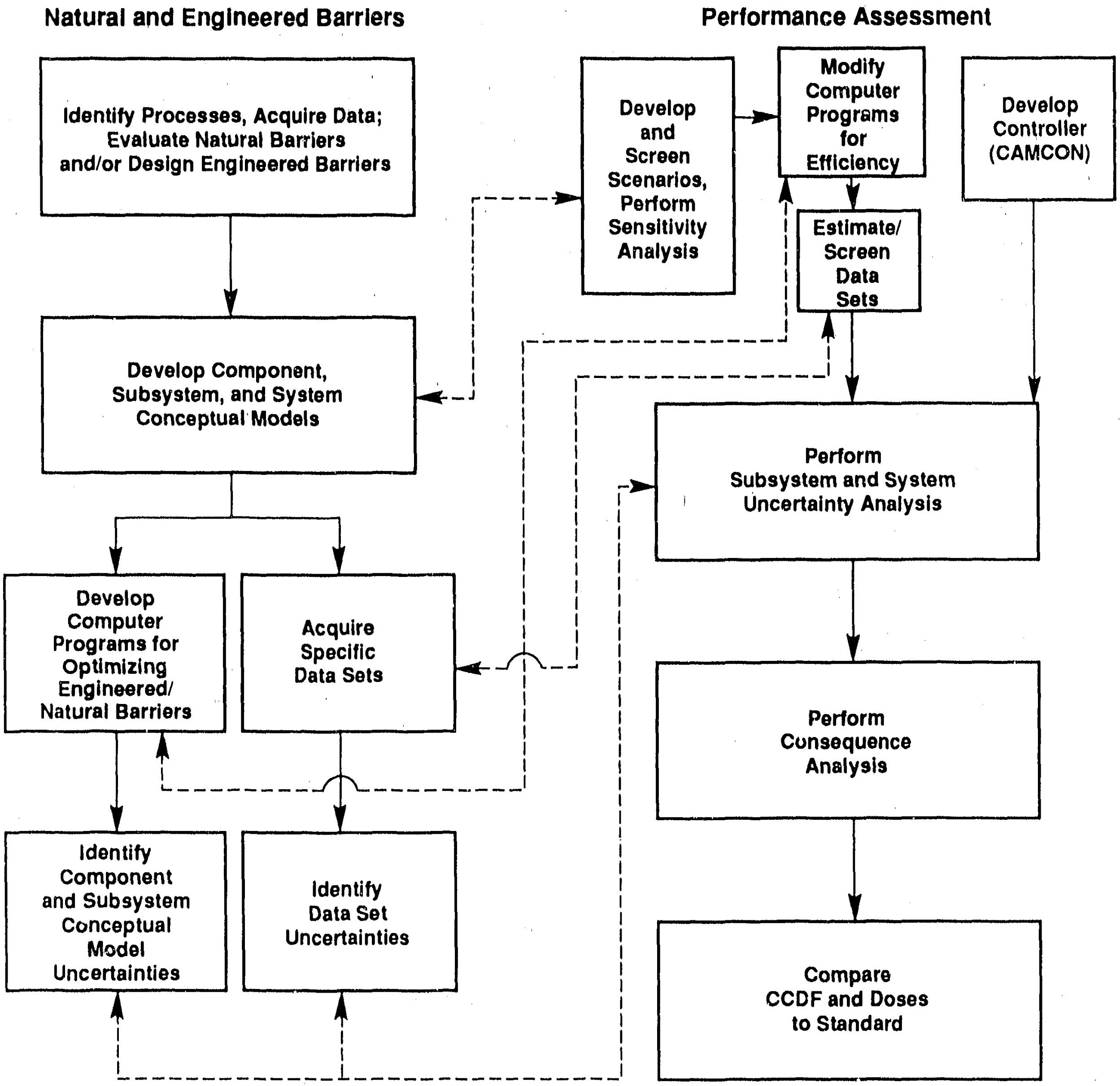

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Figure III-16. Generalized Flow Diagram for Compliance Assessment.

TABLE III-1. IMPROVEMENTS IN THE COMPLIANCE ASSESSMENT SYSTEM MADE DURING 1990

December 1989 Simulations

- Network 1-D flow and transport through Salado Formation, waste, and human-intrusion (HI) borehole
- 2-D single-porosity groundwater steady-state flow in Culebra Dolomite Member, conductivity zones sampled, LaVenue et al. (1988) domain, no climate variability, no boundary-condition uncertainty
- 1-D transport with one conductivity along entire leg, fracture porosity, and no retardation
- No brine pocket model
- No cuttings and cavings model, assumed constant for all events
- Lappin et al. (1989) data with PA-selected pdfs
- Logic diagram with 32 scenarios, 8 analyzed with one set of probabilities
- No realistic multiple intrusion scenarios
- Reference and modified waste considered, but modified waste defined from lower bounds on material properties

December 1990 Simulations

- 2-D one-phase Darcy flow of brine in Salado, interbeds, DRZ, waste, and HI-borehole fill including creep closure effects within the borehole
- 2-D two-phase Darcy flow of brine and gas in Salado, interbeds, DRZ, waste, and HI-borehole fill to time of intrusion
- 1-D two-phase Darcy flow of brine and gas in Salado, DRZ, waste, and HI-borehole fill following time of intrusion
- 2-D single-porosity groundwater transient-flow in Culebra on regional coarse-grid domain, with capability of including climate variability, recharge, and boundary-condition uncertainty
- 2-D single-porosity groundwater transient-flow in Culebra on local fine-grid domain nested in the regional domain, with capability of including climate variability and local and recharge
- 2-D radionuclide transport with retardation submodel option for discrete fractures with clay linings or dual porosity on a fine-grid domain nested in the groundwater-flow local domain
- Helical flow model for removal of cuttings and cavings
- Brine pocket model
- Most pdfs constructed using researcher-provided data and judgment
- Logic diagram with 8 scenarios, 4 analyzed with two sets of reasonably assigned probabilities
- Multiple intrusion scenarios analyzed using Poisson model for number of intrusions
- Reference and modified waste considered with modified defined as a realistic alternative: shredding metals and combustibles, repackaging with crushed salt

IV. SCENARIOS FOR COMPLIANCE ASSESSMENT

The text of Chapter IV is preceded by a synopsis that simplifies concepts presented in Chapter IV. Detailed information about those concepts is in the text following the synopsis.

Synopsis

Scenarios in Performance Assessment

The Standard addresses individual events and processes.

For a performance assessment to be complete, combinations of events and processes also must be analyzed. The combinations of events and processes are called "scenarios."

The set of scenarios must describe all reasonably possible, potentially disruptive future states of the disposal system.

Scenarios must be mutually exclusive.

Cumulative releases of radionuclides for 10,000 years must be calculated probabilistically.

The probability of occurrence of each scenario must be estimated.

Steps in Developing the WIPP Scenarios

Step 1: Identifying Events and Processes

Lists of events and processes from several sources were consolidated into a single list of 24 events and processes.

Step 2: Screening Events and Processes

Three screening criteria based on guidance in the Standard were used to screen out certain events and processes from further consideration. Screening was based on:

Site-specific physical reasonableness of the event or process.

Whether the probability of occurrence is less than 1 in 10,000 in 10,000 years.

Whether the performance of the disposal system is affected by the event or process.

14 of the 24 events and processes identified in Step 1 were screened out, and 6 of the remaining 10 must be included in all scenarios. One process will be evaluated separately. The three events retained for scenario development are:

Drilling through a waste-filled room or drift and into a brine reservoir in the underlying Castile Formation (designated E1).

Drilling into a waste-filled room or drift (designated E2).

Potash mining outside the controlled area (designated TS).

Withdrawal wells downgradient from the waste panels, which were included in earlier analyses, were not included in this analysis.

Step 3: Developing Scenarios

Remaining events and processes were combined to form scenarios through the use of a logic diagram.

At each junction within the diagram, a yes/no decision determines whether the next event or process is added to the scenario.

No time relationship between events and processes is implied by their sequence within a scenario.

Based on the assumption that the screened events and processes define all possible futures of the disposal system, the logic diagram produces scenarios that:

Are comprehensive, because all possible combinations of events and processes are developed.

Are mutually exclusive, because each scenario is a unique combination of events and processes.

Have interactions between and among events and processes incorporated in modeling.

For the WIPP, the three events remaining after screening the events and processes produce a logic diagram with 8 scenarios.

Step 4: Screening Scenarios

The purpose of scenario screening is to identify those scenarios whose exclusion from detailed consequence analysis will not have a "significant" effect on the shape or location of the final mean CCDF.

Screening criteria for scenarios are:

Physical reasonableness of the combination of events and processes.

Probability of occurrence, assumed to have the same cutoff as for screening individual events and processes.

Consequence, which in this step means probabilities of cumulative radionuclide releases to the accessible environment. Because the degree to which the mean CCDF will be affected by screening out such scenarios is difficult to estimate prior to constructing the mean CCDF, only those scenarios that have no releases should be screened out from initial consideration.

For the scenarios developed using WIPP-specific events,

All of the combinations of events are physically reasonable.

Final scenario probabilities currently are not available, so no scenarios are screened out based on probability.

Preliminary modeling results indicate that only the base-case scenario has no consequences.

Base Case Scenario

One of the products of a logic diagram is a "base-case" scenario. This scenario consists of the disposal system and all events and processes that are certain to occur in all scenarios.

The parameters that define these events and processes have ranges of values that may be the result of parameter uncertainty caused by natural variability, experimental design, or limited understanding of the processes involved.

All other scenarios are imposed on these base-case conditions.

To impose a disruptive scenario upon the base-case scenario, the parameter values of the base-case scenario are replaced by the corresponding values in the disruptive scenario. Parameters unaffected by the disruptive scenario retain their base-case values.

Descriptions of Scenarios

Base-Case Scenario

The base-case scenario represents the undisturbed performance of the disposal system.

The base-case scenario represents the disposal system at the time of decommissioning and incorporates all expected changes in the system, with associated uncertainties, for the 10,000 years of regulatory concern, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

Because of the relative stability of the natural systems within the region of the WIPP disposal system, all naturally occurring events and processes that are likely to occur are part of the base-case scenario.

The scenario is described as follows:

> After the repository is filled with waste, the disposal rooms and drifts in the panels are backfilled, and seals are emplaced in the access passageways to the panels.

Because the pressure within the disposal rooms and drifts is less than the pressure of the host rock, salt will creep into these openings. The pressures exerted on the backfill by the salt creep are expected to consolidate this material to a state with properties similar to those of the surrounding host rock.

Some gases are expected to be generated by biodegradation of organic material in the waste and waste containers, corrosion of metals, and radiolysis.

Migration of radionuclides depends on the degree of brine saturation within the repository.

Gas pressure may prevent brine inflow and desaturate the nearby host rock. These conditions in addition to brine consumption by corrosion and microbial activity would result in decreased saturation of the waste and backfill and a lower potential for transport of radionuclides.

Two pathways are likely to dominate the migration of radionuclides to the accessible environment. One path is directly vertical through the host rock to the Culebra Dolomite, then horizontally to the accessible environment. The other pathway is horizontally through an underlying marker bed to the base of one or more access shafts, up the shaft(s) to the Culebra Dolomite, then horizontally to the accessible environment.

Scenario E2

Scenario E2 consists of a single borehole that penetrates to or through a waste-filled room or passageway in a panel.

The scenario consists of the following components:

After decommissioning, moisture in the waste and from the surrounding rock allows gas generation to occur from various sources.

During drilling, radionuclides are released directly to the surface as the drill penetrates a room or drift and intersects drums or boxes of waste. Some waste is ground up and is transported to the surface by circulating drilling fluid.

After abandonment, the hole is plugged above the Culebra Dolomite, and the plug does not degrade. A plug below the Culebra Dolomite is assumed to degrade.

If gases vent up the borehole during drilling, a reduction in pressure within the room or drift allows brine to flow in from the surrounding rock.

Inflow in sufficient quantities could force brine up the borehole through a degraded borehole plug to the Culebra Dolomite for transport to the accessible environment.

Scenario E1

Scenario E1 consists of a single borehole that penetrates through a waste-filled room or drift and continues into or through a pressurized brine reservoir in the Castile Formation.

The scenario differs from E2 in the following components:

After the borehole is plugged and abandoned, the pressure in the brine reservoir is assumed to be sufficient to drive flow up the borehole and through a degraded plug. Flow is diverted into the Culebra Dolomite because the plug above the Culebra Dolomite does not degrade.

Radionuclides from the room or drift can be incorporated into the brine as the brine circulates through the waste adjacent to the borehole.

Upon reaching the Culebra Dolomite, the contaminated brine flows toward the accessible environment.

The flow of brine from the brine reservoir eventually stops, and the scenario continues with the same characteristics as E2.

Scenario E1E2

Scenario E1E2 consists of two boreholes that penetrate waste-filled rooms or drifts in the same panel. One of the boreholes also penetrates a pressurized brine reservoir in the Castile Formation.

The borehole that penetrates the pressurized brine is plugged between the repository and the Culebra Dolomite Member, forcing into the room all the brine flowing up the borehole. The other borehole is plugged above the Culebra Dolomite Member, forcing into the Culebra Dolomite all the brine flowing up this borehole.

The scenario includes the same components as E1 and E2. Additional components are dependent on the sequence in which the boreholes are drilled.

> The plug between the repository and the Culebra Dolomite in the borehole that penetrates the pressurized brine does not degrade, allowing brine flowing up the hole to enter the repository but not leave the repository until the second borehole penetrates the same panel. The second borehole forms a pathway for brine from the pressurized brine reservoir to flow through rooms or drifts, or both, to this new hole and up to the Culebra Dolomite. The plug above the Culebra Dolomite in the second hole does not degrade, so flow is diverted into that unit.
>
> If the hole that does not penetrate the pressurized brine reservoir is drilled first, gas and/or fluid pressure is relieved, followed by groundwater flow and transport of radionuclides up the borehole as a result of brine inflow into the panel from the surrounding rock.
>
> Flow is diverted into the Culebra Dolomite Member by the plug located above this unit.
>
> Subsequent drilling and plugging of the borehole that penetrates the pressurized brine reservoir results in flow through the repository and up the other borehole.
>
> After the driving pressure of the brine reservoir is depleted, Scenario E1E2 reverts to Scenario E2, because the borehole that penetrates the pressurized brine no longer contributes to flow and transport.

Multiple Intrusions

Each simulation of a human intrusion scenario could include between one and fifteen intrusion events. The timing and number of events is part of the uncertainty analysis.

Scenario Probability Assignments

Estimates of scenario probabilities were made for demonstration purposes so that a mean CCDF could be constructed.

Probability assignments for compliance assessment will rely on expert judgment. Formal application of an expert-judgment elicitation procedure is in progress.

A performance assessment addresses the Containment Requirements § 191.13(a) of the Standard by completing a series of analyses that predict the performance of the disposal system for 10,000 years after decommissioning and compares the performance to specific criteria within the Standard. Although the definition of performance assessment in the Standard refers only to events and processes that might affect the disposal system, the occurrence of an event or process at a disposal site does not preclude the occurrence of additional different events and/or processes at or near the same location. For the analyses in a performance assessment to be complete, the combinations of events and processes that define possible future states of the disposal system must be included. Combinations of events and processes are referred to as scenarios.

Appendix B of the Standard states that wherever practicable, the results of the performance assessments will be assembled into a CCDF, which is interpreted in this document to be a mean CCDF (see Chapter III), in order to determine compliance. In order to construct a mean CCDF for determining compliance with the Containment Requirements, four criteria must be met: (1) the set of scenarios analyzed must describe all reasonably possible future states of the disposal system, (2) the scenarios in the analyses must be mutually exclusive so that radionuclide releases and probabilities of occurrence can be associated with specific scenarios, (3) the cumulative releases of radionuclides (consequences) of each scenario must be determined, and (4) the probability of occurrence of each scenario must be estimated. Because performance assessments are iterative analyses, the results of preliminary analyses may suggest areas for additional research, which could in turn suggest new events and processes for inclusion in scenarios.

Identifying all possible combinations of events and processes that could affect a disposal system would result in an extremely large number of scenarios, most of which would have little or no effect on the performance of the disposal system. Guidance to the Standard allows certain events and processes, and by implication scenarios, to be excluded from the performance-assessment analyses. Exclusion criteria are low probability and low consequence. In addition, exploratory drilling for natural resources is the most severe type of human intrusion considered. Each criterion is described in Appendix B of the Standard (reproduced in Appendix A of this report).

Scenarios that are within the scope of Appendix B of the Standard and meet the requirements for constructing a mean CCDF must be identified. Cranwell et al. (1990) developed a scenario-selection procedure that consists of five steps. These steps are: (1) compiling or adopting a "comprehensive" list of events and processes that potentially could affect the disposal system, (2) classifying the events and processes to aid in completeness arguments, (3) screening the events and processes to identify those that can be eliminated from consideration in the performance assessment, (4) developing scenarios by combining the events and processes that remain after screening, and (5) screening scenarios to identify those that have little or no effect on the shape or location of the mean CCDF. This scenario-selection procedure has been adopted for the WIPP Performance Assessment, and a summary of its implementation follows.

Identifying Events and Processes

Several reports have identified events and processes that could affect the integrity of a generic disposal system (Burkholder, 1980; IAEA, 1983; Cranwell et al., 1990) and for specific locations (Claiborne and Gera, 1974; Bingham and Barr, 1979). The difference between an event and a process is the time interval over which a phenomenon occurs relative to the time frame of interest. Events occur over relatively short time intervals, and processes occur over much longer relative time intervals. The distinction between events and processes is not rigid. For example, in the life of a person, a volcanic eruptive cycle that lasts several years may be classified as a process, but in the 10,000 years of regulatory concern for the repository, this same cycle may be considered as an event. Phenomena that occur instantaneously or within a relatively short time interval are considered to be events, and phenomena that occur over a significant portion of the 10,000 years are considered to be processes.

Hunter (1989) examined the above references and consolidated the events and processes by identifying 24 to be evaluated for performance assessment in light of the 1985 Standard.

Classifying Events and Processes

This step in the scenario-selection procedure is optional. The purposes for including this step in the procedure were to assist in organizing the events and processes and to provide some insights when developing conceptual models of the disposal system. Categories in the classification schemes for the generic lists mentioned in Step 1 are similar and can be identified as naturally occurring, human induced, and waste and repository induced. Hunter (1989) did not classify the events identified in Step 1. This lack of classification has not affected the scenario selection.

Screening Events and Processes

Three screening criteria follow the guidelines in the Standard: physical reasonableness, probability of occurrence, and potential consequence (at this stage in the procedure consequence means affecting the disposal system). According to Appendix B of the Standard, events and processes that are estimated to have less than one chance in 10,000 of occurring in 10,000 years do not have to be considered. Events and processes with higher probabilities of occurrence than this value also can be omitted if there is reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed. Physical reasonableness as a screening criterion is a low probability judgment based on qualitative reasoning derived from informal expert judgment. In the absence of sufficient data to use a mathematical probability technique or a formal expert-elicitation technique, a logical argument, possibly with supporting calculations, can be presented as to the lack of physical reasonableness for a particular event or process occurring during the period of regulatory concern. In addition to these screening criteria, Appendix B of the Standard limits the severity of human intrusion.

EVENTS AND PROCESSES SCREENED OUT

The screening criteria used by Hunter (1989) were physical reasonableness and to a lesser extent probability of occurrence. Table IV-1 lists the events and processes screened out of the performance assessment. This section summarizes Hunter's (1989) analyses of these events and processes, describing why each was screened out:

Dissolution Processes

Hunter (1989) screened out four dissolution processes: dissolution by fresh water, migration of the Rustler-Salado residuum, vertical dissolution, and breccia pipe formation. The reasons for dismissing these processes follow.

TABLE IV-1. EVENTS AND PROCESSES SCREENED OUT FROM FURTHER ANALYSIS

Dissolution Other Than Leaching
Breccia-Pipe Formation
Migration of Residuum
Migration of Brine Inclusions
Induced Diapirism
Exhumation, Sedimentation
Faulting
Diffusion (to Accessible Environment)

Glaciation
Igneous Intrusion
Meteorite Impact
Sabotage, Warfare
Subsidence*
Thermal Effects from Waste
Uplift of Surface

*Subsidence caused by potash mining has been retained.
Source: Modified from Hunter, 1989.

Dissolution of the repository horizon by fresh water (except for solution mining) was screened out by Hunter (1989) because it is physically unreasonable. No natural mechanism exists to introduce fresh water into the repository horizon.

An increase in the horizontal extent of the Rustler-Salado residuum, which is associated with Nash Draw, was screened out by Hunter (1989) on the basis of negligible consequence. Extrapolation of estimated horizontal dissolution rates (Bingham and Barr, 1979; U.S. DOE, 1980a) indicate that the residuum contained in the residuum would move only 0.13 km (0.08 mi) closer to the repository in 10,000 years; the resulting effect on consequences of such a migration is well within the uncertainty of the consequence analysis.

Vertical dissolution was screened out by Hunter (1989) because it will have no consequence on the regulatory time scale. Before vertical dissolution could begin to remove the salt directly above the repository at the WIPP site, the dissolution front would have to migrate eastward from its present position approximately at Nash Draw and arrive at the site. Studies indicate that vertical dissolution would not expose a repository at WIPP for 2 to 3 million years (Bingham and Barr, 1979; U.S. DOE, 1980a).

Breccia pipes were screened out by Hunter (1989) for several reasons. Hunter (1989) concluded that the occurrence of a breccia pipe at the WIPP is not physically reasonable for the following reasons: (1) no breccia pipes have occurred at locations geologically similar to the WIPP; (2) no confirmed mechanism exists for the formation of breccia pipes at the WIPP; and (3) even if such a mechanism could be postulated, the time of formation would be longer than the 10,000-year regulatory period. Granting for the sake of argument that a breccia pipe might form in the vicinity of the WIPP, calculations by Cranwell et al. (1990) show that the probability of intersecting the repository is about the same as the cutoff in the Standard. Preliminary analysis of consequences of a breccia pipe forming beneath the repository (Spiegler, 1982) has shown negligible, or even zero, consequences during the 10,000-year regulatory period. Breccia pipes several kilometers away from the WIPP could cause leakage into or from overlying hydrostratigraphic units, or both, in which case effects on downgradient transport from the WIPP are similar to those of subsidence and are retained for consideration.

Migration of Intracrystalline Brine Inclusions

Hunter (1989) determined that no treatment of migrating intracrystalline brine inclusions is warranted because migration is physically unreasonable. Though brine inclusions have been shown to migrate in response to thermal gradients (Shefelbine, 1982), experiments simulating the disposal of RH-TRU waste, which generates moderate amounts of heat (Tyler et al., 1988), have shown that little or no brine migrates into the experimental test holes in response to the imposed thermal gradients.

Induced Diapirism

Induced diapirism in the salt, a process by which heat generated by radioactive waste in a salt repository could cause a loss of containment through the creation of buoyant forces, is physically unreasonable and therefore was not retained by Hunter (1989) for consequence analysis. Even calculations based on the much higher heat loadings associated with high-level waste have shown that there would be no significant vertical movement of waste through the salt (U.S. DOE, 1980a).

Diffusion (to Accessible Environment)

Hunter (1989) found that diffusion of significant amounts of waste to the accessible environment is physically unreasonable. A diffusion scenario that assumed a stagnant pool connecting the Rustler Formation with the repository area was modeled (U.S. DOE, 1980a). This model, which conservatively assumed that a mechanism exists to allow such a stagnant pool to develop and remain for 10,000 years and that WIPP waste would be as soluble as salt, indicates that releases would be negligibly small: less than 0.000003 of the waste in 10,000 years.

Exhumation or Sedimentation

Hunter (1989) found that neither exhumation by erosional processes nor significant sedimentation are reasonable within 10,000 years. Claiborne and Gera (1974) concluded that exhumation of waste at the WIPP could be neglected because several hundred thousand to several million years would be required. Other studies also concluded that the consequences of erosion and sedimentation were negligible (Logan and Berbano, 1978; Bingham and Barr, 1979; Arthur D. Little, Inc., 1980; Cranwell et al., 1990; Proske, 1977).

Faulting

Hunter (1989) screened faulting from the WIPP performance assessment on the bases of physical unreasonableness and low probability. The absence of faulting in the vicinity of the WIPP during the past 200 million years suggests that faulting during the next 10,000 years would be physically unreasonable. Even if one were to assume faulting, the probability would be extremely small. Claiborne and Gera (1974) calculated the likelihood of a fault intercepting the repository to be 4×10^{-11} per year.

Subsidence

Three kinds of subsidence might occur at and near the WIPP: subsidence of the overlying rock into the repository, subsidence as a result of conventional or solution mining for potash, or regional subsidence as a result of oil and gas extraction. Subsidence could in turn conceivably affect the disposal system in three ways: by increasing the hydraulic conductivity of the Salado Formation, by creating fractures through the Salado Formation, or by disturbing the surface drainage and groundwater flow in overlying units.

Increased hydraulic conductivity and transport through fractures in the Salado Formation that could result from subsidence were screened out on the basis of negligible consequence. Calculations show that the initial void volume in the waste panels represents only about 0.002 of the volume of the overlying salt (Hunter, 1989). Any alteration of the hydraulic conductivity resulting from subsidence over the waste panels will be restricted to the immediate area of the panels.

The possibility that void volume will translate to the overlying salt as fractures rather than uniformly increased porosity is considered unlikely and has been screened out by Hunter (1989) as physically unreasonable. Because long-term salt deformation at depth will occur by creep, fracturing is considered to be unlikely (Bingham and Barr, 1979). Observations in nearby potash mines with two levels of extraction show that subsidence into the lower mined area results in flexure, not fracture, of the upper horizons of the potash zones. However, if later investigations show that the Salado Formation may fracture in the far field after excavation of the repository, fractures will be reconsidered.

Increased releases as a result of disruption of surface drainage directly above the repository were considered to be physically unreasonable by Hunter (1989). The DOE (1980a) calculated that surface subsidence for the WIPP repository would be less than 2 feet (0.6 m) and pointed out that there is no integrated surface drainage to be disrupted (Hunter, 1989).

If potash mining occurs outside the controlled area of the WIPP, the comparatively higher extraction ratios and reduced backfill of the potash mines could cause a higher level of subsidence. This subsidence could form catchment basins for rainfall and allow recharge to the Culebra Dolomite and the unsaturated zone (Guzowski, 1990). Thus, this event is retained for additional evaluation.

Other Events and Processes

Glacial loading was screened out by Hunter (1989), because no such effects are expected at the WIPP (Bingham and Barr, 1979). Detailed geologic studies have revealed no evidence suggesting that southeastern New Mexico has ever been glaciated. Alpine glaciation, if it were to occur during a future ice age, would be too distant to affect WIPP. Though glacial loading was considered physically unreasonable, climatic changes accompanying glaciation were retained.

Hunter (1989) screened out igneous intrusion by a lamprophyre dike because of low probability. The probability of such an event was calculated to be less than 2 x 10^{-6} in 10,000 years (Logan et al., 1982), much less than the EPA cutoff.

Meteorites were screened out by Hunter (1989) from further investigation on the basis of low probability. All calculations (Claiborne and Gera, 1974; Bingham and Barr, 1979; Cranwell et al., 1990; Arthur D. Little, Inc., 1980) on the probability of meteorite impact causing a release of waste from the WIPP have probabilities less than 3 x 10^{-7} per year.

An analysis of release from the WIPP disposal system by sabotage or warfare is unnecessary according to the Standard because these events are more severe than exploratory drilling. Futhermore, Claiborne and Gera (1974) and Bingham and Barr (1979) concluded that neither sabotage nor warfare would present a credible threat to the repository (Hunter, 1989).

Thermal effects were screened out by Hunter (1989) on the basis of negligible consequence. The waste scheduled for emplacement will generate very little heat—less than 2°C (3.6°F) at 80 years after emplacement. Temperatures will drop steadily after that. The maximum surface uplift caused by heat expansion was calculated to be less than one centimeter (0.4 in) (U.S. DOE, 1980a).

EVENTS RETAINED FOR PERFORMANCE ASSESSMENT

Eight events and processes were not screened out by Hunter (1989). Each of the processes, except for nuclear criticality, will occur to at least some degree in all possible futures, and as a result, each of these processes must be part of all scenarios. By being part of all scenarios, the processes are part of the conceptual model of the disposal system. Nuclear criticality will be evaluated separately. If this process occurs under some but not all conditions, this process will be included in a revision to scenario development.

The descriptions of the events that were not screened out by Hunter (1989) were modified slightly by Guzowski (1990) to make them more amenable to the early stages of probabilistic modeling for performance assessment. These events are: (1) drilling an exploratory borehole through a waste-filled room or drift and into a pressurized brine reservoir in the underlying Castile Formation, E1; (2) drilling an exploratory borehole into a waste-filled room or drift, E2; and (3) potash mining outside of the controlled area that results in surface subsidence and the formation of a catch basin for runoff, TS. In Guzowski (1990), an additional event was included in scenario development. The drilling of one or more withdrawal wells (E3) to supply water from the Culebra Dolomite or other shallow units to watering tanks for cattle was assumed to occur downgradient from the waste panels. Because the Culebra Dolomite is the most likely source of shallow water in the area of the panels and contains highly saline water within approximately 5 km (3 mi) of the panels (Lappin et al., 1989), withdrawal wells are not included in scenario development for a preliminary comparison with the Standard.

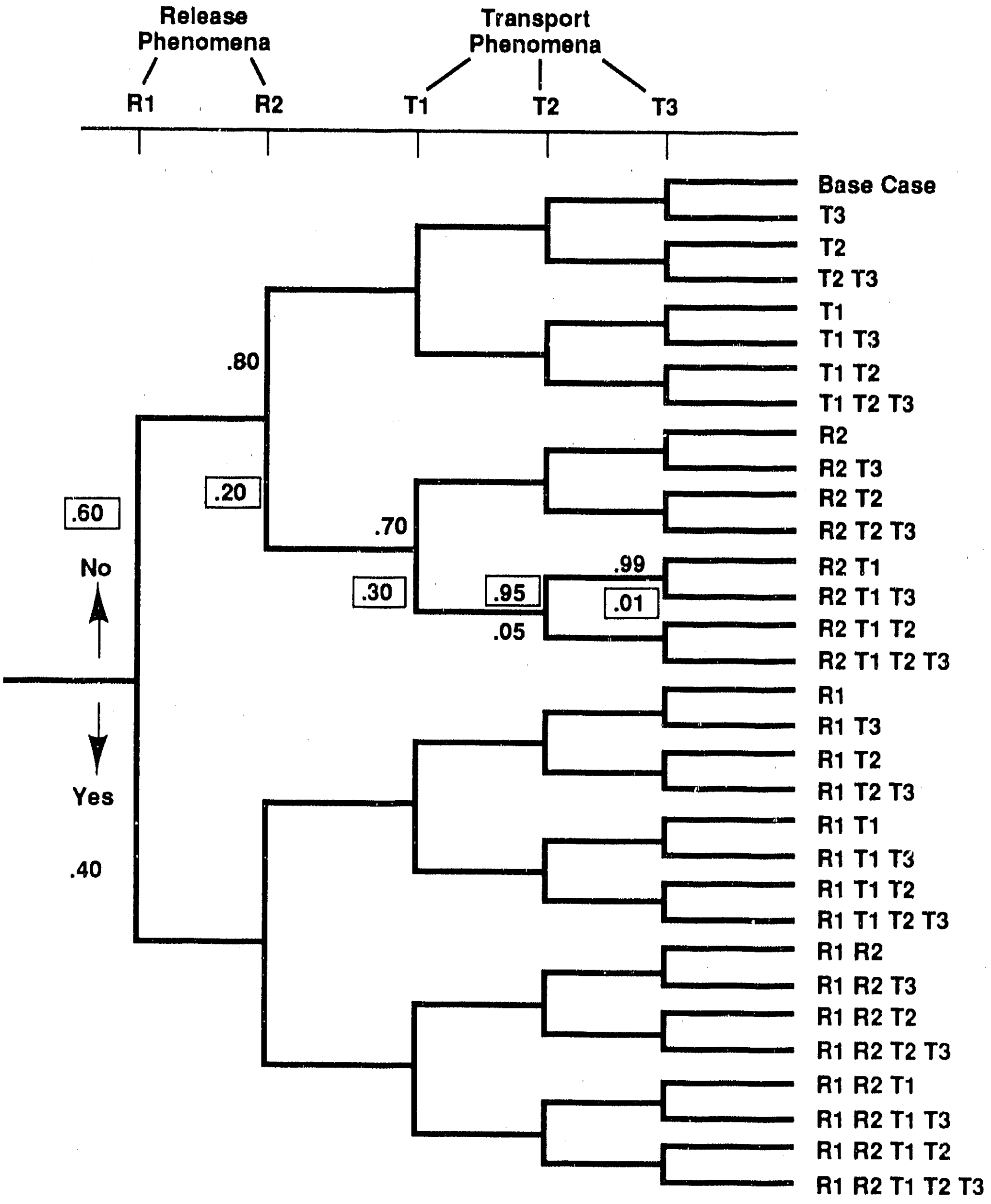
Developing Scenarios

To construct a CCDF, the scenarios used in the performance assessment must be comprehensive and mutually exclusive. An earlier approach to scenario development combined events and processes through the use of event trees (Bingham and Barr, 1979; Hunter, 1983; Hunter et al., 1982; Hunter et al., 1983). According to McCormick (1981), an event tree is an inductive logic method for identifying possible outcomes of a given initiating event. Once the systems that can be utilized after a failure are identified and enumerated, the failure and success states are identified through bifurcations within the tree. If partial failures are considered, a greater number of branches is needed. The result is an event tree that provides accident sequences associated with an initiating event. Analyses of this type commonly are used to assess potential accidents at nuclear power plants (e.g., U.S. NRC, 1975).

Event trees were found not to be suitable for natural systems (Burkholder, 1980). The disadvantages of using event trees to develop scenarios for natural systems are: (1) the imposed temporal relationship of events and processes to one another, (2) the apparent arbitrariness of branching within the tree, (3) the inability to assure completeness of the final scenario set, and (4) the inability of the tree to handle feedback loops, whereby development along one branch may change the system to the point where the branching that resulted in that scenario will be reversed (Guzowski, 1990).

Event trees for scenario development have not been able to produce reasonable numbers of well-defined and mutually exclusive scenarios that can be analyzed probabilistically to address the current formulation of the Standard (Guzowski, 1990). An alternative approach addresses these problems through logic diagrams (Figure IV-1) (Cranwell et al., 1990). In the logic diagram, no temporal relationship between events and processes is implied by their sequence across the top of the diagram. Parameter values, time of occurrence, and location of occurrence are not used to define the events and processes, and parameter uncertainty is incorporated directly into the database. At each junction within the diagram a yes/no decision is made as to whether the next event or process is added to the scenario. As a result, each scenario consists of a combination of occurrence and nonoccurrence of all events and processes that survive screening (Cranwell et al., 1990). To simplify scenario notation, only the events and processes that occur are used to identify the scenario. Based on the assumption that the events and processes remaining after screening define all possible futures of the disposal system that are important for a probabilistic assessment, the logic diagram produces scenarios that are comprehensive, because all possible combinations of events and processes are developed; the scenarios are mutually exclusive, because each scenario is a unique set of events and processes; and feedback loops may be incorporated in models of the combinations of events and processes. The time of occurrence for an event or process can be sampled as a variable during uncertainty analyses.

Figure IV-2 is the logic diagram for constructing all of the possible combinations of the three events (E1, E2, and TS) that survived the screening process for the WIPP. The base case represents the undisturbed condition, which is the expected behavior of the disposal system without disruption by human intrusion. Because locations of pressurized brine reservoirs beneath



☐ **Indicates Examples of Probability Values Needed to Determine Probability of Scenario R2T1T3**

Probability of R2T1T3 = (.60)(.20)(.30)(.95)(.01) = 3.4 x 10^{-4}

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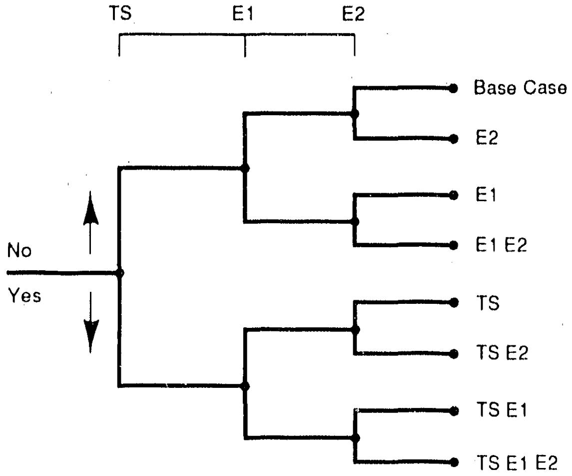
Figure IV-1. Example of a Logic Diagram with Two Release (R) and Three Transport (T) Phenomena for the Construction of Scenarios (after Cranwell et al., 1990), Illustrating Scenario Probability Assignment.



TS - Subsidence Resulting from Solution Mining of Potash
E1 - Drilling through Room and Brine Pocket
E2 - Drilling through or into a Room

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3 Figure IV-2. Potential Scenarios for the WIPP Disposal System.

the waste panels have been mapped by geophysical techniques, a modification to scenario development in some simulations for this assessment incorporates the reservoirs into the conceptual model of the disposal system, thereby limiting human intrusion at the panels to a single event. In this approach, whether the intrusion penetrates the brine reservoir depends on drilling depth and surface location of the well head. This redefinition of events simplifies the logic diagram by removing one event, and simplifies the process of evaluating multiple borehole intrusions (see section on "Multiple Intrusion Events").

Screening Scenarios

The purpose of scenario screening is to identify those scenarios that will have no or a minimal impact on the shape and/or location of the mean CCDF. By inference, the criteria used to screen combinations of events and processes (scenarios) are similar to those criteria used to screen individual events and processes. These criteria are physical reasonableness of the combinations of events and processes, probability of occurrence of the scenario, and consequence (probabilities of cumulative radionuclide releases to the accessible environment).

Whereas the events and processes for constructing scenarios are physically reasonable, certain combinations of events and processes may not be reasonable. If parameter values and specific locations of occurrence are not used to define the events and processes, this screening criterion generally will not be a factor in scenario screening.

The probability of occurrence for a scenario is determined by combining the probabilities of occurrence and nonoccurrence from the events and processes that make up the scenario. A mechanical approach to determining scenario probabilities can be implemented by assigning the probability of occurrence and nonoccurrence for each event and process to the appropriate "yes" and "no" legs at each bifurcation in the logic diagram (Figure IV-1). The probability of a scenario is the product of the probabilities along the pathway through the logic diagram that defines that scenario (see Figure IV-1 for an example). Based on the probability criterion in Appendix B of the Standard for screening out individual events and processes, scenarios with probabilities of occurrence of less than one chance in 10,000 in 10,000 years will not affect whether the mean CCDF complies with or violates the Standard, and therefore, consequence calculations are not necessary.

A final screening criterion is consequence, which in this step of the procedure means integrated discharge to the accessible environment for 10,000 years. By inferring that the guidance in Appendix B of the Standard for individual events and processes also applies to scenarios, scenarios whose probability of occurrence is less than the cutoff in Appendix B can be eliminated from further consideration if their omission would not significantly change the final mean CCDF. Because the degree to which the mean CCDF will be affected by omitting such scenarios is difficult to estimate prior to constructing CCDFs, only those scenarios that have no releases should be screened out from additional consequence calculations. If significant changes are made to the database, the conceptual models, or mathematical models of the disposal system, the latter scenarios should be rescreened.

In implementing this step of the procedure for this preliminary WIPP performance assessment, no scenarios were screened out. Because parameter values did not define the events, all combinations of events in the scenarios are physically reasonable. Because final scenario probabilities have not been estimated, no scenarios were screened out on the basis of low probability of occurrence. Final calculations of consequences have not been completed, so no scenarios were screened out on the basis of this criterion.

Descriptions

This section describes the scenarios retained for consequence analysis.

UNDISTURBED PERFORMANCE SCENARIO

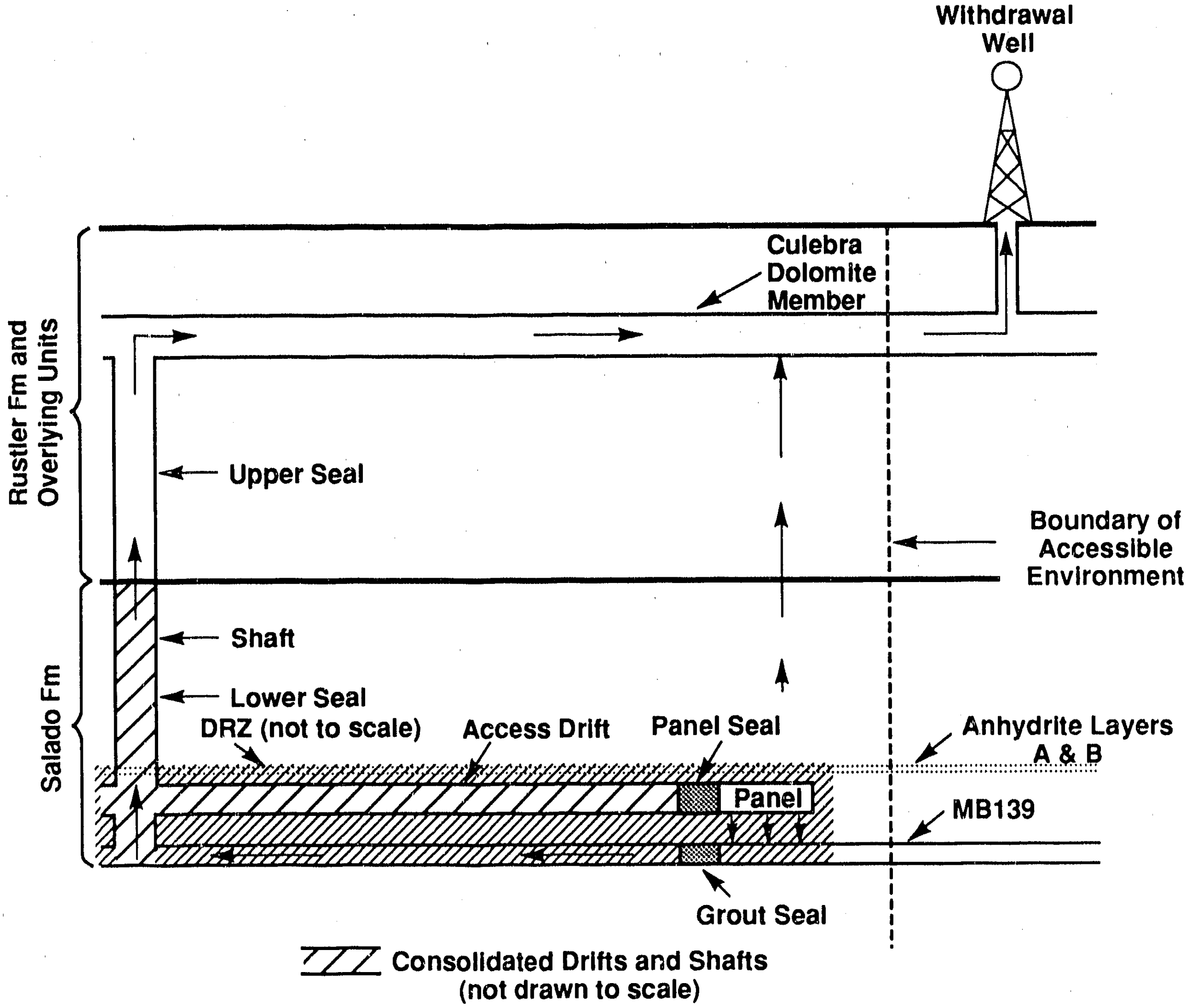
The Individual Protection Requirements of the Standard (§ 191.15) call for the disposal system to limit annual doses to individuals for 1,000 years after disposal assuming undisturbed performance of the disposal system. Undisturbed performance is also the base case of the scenario-development methodology (Cranwell et al., 1990; Guzowski, 1990). Although undisturbed performance is not mentioned in the Containment Requirements (§ 191.13), undisturbed performance is not precluded from the containment calculations.

As defined in the Standard (§ 191.12(p)), "'Undisturbed performance' means the predicted behavior of a disposal system, including the consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." Duration of this performance is not limited by the definition. The base-case scenario describes the disposal system from the time of decommissioning and incorporates all expected changes in the system and associated uncertainties for the 10,000 years of concern for § 191.13. Expected changes are assumed to result from events and processes that are certain to occur without disrupting the disposal system. The Standard does not provide a definition of unlikely natural events to be excluded from undisturbed performance nor, by implication, likely natural events to be included. Because of the relative stability of the natural systems within the region of the WIPP disposal system, all naturally occurring events and processes that will occur are part of the base-case scenario and are nondisruptive. These conditions represent undisturbed performance (Marietta et al., 1989).

Base-Case Scenario

After the repository is filled with waste, the disposal rooms and drifts in the panels are backfilled and seals are emplaced in the access drifts to the panels (Figure IV-3). While excavations are open, the salt creeps inward because of the decrease in confining pressure on the salt around the rooms. The movement of floors upward and ceilings downward into rooms and drifts fractures the more brittle underlying anhydrite in MB139 and overlying anhydrite layers A and B. The anhydrite is expected to fracture directly beneath and above excavated rooms and drifts but not beneath or above the pillars because of the overburden pressure on the pillars. To control potential radionuclide migration through MB139, seals are emplaced in MB139 directly beneath the panel seals (Stormont et al., 1987; Borns and Stormont, 1988; Nowak et al., 1990). Access drifts and the lower parts of shafts are backfilled with salt. Because of the high lithostatic pressures at the repository depth, salt creep is expected to exert sufficient pressure on the backfill to consolidate the material into low-conductivity seals with properties similar to those of the host rock. The upper parts of the shafts are also backfilled with salt, but pressure exerted by salt creep on backfill is not expected to be sufficient to cause the same degree of consolidation as is expected in lower portions of the shafts (Marietta et al., 1989).

Before the amount and direction of groundwater flow and radionuclide release from the repository can be determined, gas generation must be considered. Some waste and some waste containers will be composed of organic material. Because microbes transported into the repository with the waste are expected to be viable under sealed-repository conditions (Brush and Anderson, 1988a), organic material in the repository will biodegrade with concomitant generation of gases. In addition, moisture in the repository, either brought in with waste or seeping in from the Salado Formation, can corrode metals in the waste and metallic waste containers themselves, with gas generated as a by-product. Radiolysis also will generate gases. The time period over which gases will be generated is uncertain. Each of these processes is dependent on the availability of water. The humidity required for microbiological activity and whether or not saturated conditions are required for corrosion and radiolysis have not been established. Moisture and microbes in waste will generate some gas prior to waste emplacement in the repository. After emplacement, the amount and rate of gas generation will depend on such



3 Figure IV-3. Conceptual Model Used in Simulating Undisturbed Performance.

factors as microbe metabolisms; relationships between gas pressure, brine inflow, room closure, and backfill and waste consolidation; and the degree to which reactions attain completion (Marietta et al., 1989).

Radionuclide migration depends on the degree of saturation within the repository. Gas pressure resulting from microbial activity and corrosion may prevent brine inflow and desaturate the nearby Salado Formation, MB139, and anhydrite layers A and B. These conditions, in addition to the consumption of water by anoxic corrosion and possibly microbial activity, also would result in a decrease in the amount of water in the waste and backfill and a lower potential for radionuclide transport. For this assessment, radionuclide transport calculations for the undisturbed scenario conservatively assume that the waste and backfill are fully saturated from the time of final consolidation, and transport is simulated for the entire period of regulatory concern. Separate two-phase (gas and brine) simulations of undisturbed conditions support this assumption.

Assuming fully brine-saturated conditions, two pathways for groundwater flow and radionuclide transport likely will dominate the disposal system (Figure IV-3). In the first path, radionuclides enter MB139, either through fractures in salt or directly as a result of rooms and drifts intersecting the marker bed during construction or room closure. Because material in the upper shaft is expected to be poorly consolidated, the hydraulic pressure at the junction of the upper and lower parts of the shaft seals is assumed to approximate the pressure head of the Culebra Dolomite Member. As a result, the pressure gradient tends to force radionuclide-bearing groundwater from MB139 beneath the panel through the seal in the marker bed, along the fractures in MB139 to the base of the shaft, up the shaft to the Culebra Dolomite Member, and downgradient in the Culebra to the accessible environment. Relative motion during salt creep and resulting backfill consolidation prevent MB139 from returning to its original position and the salt-creep induced fractures do not completely close. Flow is through MB139 instead of through the overlying access drift because of the substantially higher hydraulic conductivity in MB139. Flow in MB139 is to the north through the seal rather than to the south down the pre-excavation hydraulic gradient within MB139, because the pressure drop to the north is greater after excavation, and the flow to the south would be impeded by extremely low permeability of the intact marker bed. Therefore, the horizontal path directly through MB139 to the accessible environment is not included for this assessment, but this path may be considered for other analyses (Marietta et al., 1989).

The other dominant path is assumed to be from the repository vertically through the intact Salado Formation toward the Culebra Dolomite Member (Figure IV-3) (Lappin et al., 1989). This path has the largest pressure decline over the shortest distance of any path. In addition, large potential exists for radionuclides to leave the repository along this path because of the large horizontal cross-sectional area of the waste-bearing rooms and drifts in the repository. Two other pathways, one horizontally through the Salado and another through the consolidated drifts and panel seals, are less important than the pathway through MB139 (Lappin et al., 1989). Only the MB139 pathway to the north is considered here (Marietta et al., 1989).

The methodology can determine pathways to individuals and calculate doses to humans if a release pathway is added. The pathway used in an earlier analysis (Lappin et al., 1989) is described in the next section. Because undisturbed performance releases no radionuclides in 1,000 years, these calculations are not necessary for this scenario (Marietta et al., 1989).

Release at a Livestock Pond

Livestock wells were assumed to be located downgradient from the repository for earlier analyses (Lappin et al., 1989), because these wells were believed to be the only realistic pathway for radionuclides to reach the surface under undisturbed conditions. Radionuclide-bearing brine could seep through and around grouted seals in the marker bed, and migrate through the part of MB139 that underlies drift excavations to the bottom of the sealed shafts. This material is then assumed to continue to migrate up through the lower seal system due to the pressure gradient between the waste panels and the Culebra Dolomite Member. Material introduced into the Culebra Dolomite is entrained in the groundwater. In order to provide a route to man, an active livestock well is assumed to penetrate the Culebra Dolomite downgradient from the sealed shafts. Radionuclides migrate through the Culebra groundwater to the livestock well where water is pumped to the surface for cattle to drink. This is the beginning of the biological pathway to humans via a beef ingestion route (Lappin et al., 1989). Other possible pathways originating from the full and later dry stock pond exist and will be considered, but for undisturbed conditions, any possibility requires a pumping well route to the surface. Because no radionuclides traverse this route is not completed in 1,000 years, no need exists to consider other possible pathways for § 191.15 at this time, although the response to the remand may change this position.

HUMAN INTRUSION SCENARIOS

Appendix B of the Standard (U.S. EPA, 1985) provides guidance on a number of factors concerning human intrusion. The Appendix B section entitled "Institutional Controls" states that active controls cannot be assumed to prevent or reduce radionuclide releases for more than 100 years after disposal. Passive institutional controls can be assumed to deter systematic and persistent exploitation and to reduce the likelihood of inadvertent intrusion, but these controls cannot eliminate the chance of inadvertent intrusion. The section in Appendix B of the Standard entitled "Consideration of Inadvertent Human Intrusion into Geologic Repositories" suggests that exploratory drilling for resources can be the most severe form of human intrusion considered. The Appendix B section on "Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories" suggests that the likelihood and consequence of drilling should be based on site-specific factors. In keeping with the guidance, this assessment includes scenarios that contain human-intrusion events (Marietta et al., 1989).

Intrusion Borehole into a Room or Drift (Scenario E2)

Scenario E2 consists of a single borehole that penetrates to or through a waste-filled room or drift in a panel (Figure IV-4). The borehole does not intersect pressurized brine or any other important source of water. The hole is abandoned after a plug is emplaced above the Culebra Dolomite Member. The drilling mud that remains in the borehole is assumed to degrade into sand-like material. The borehole below the plug in the Salado Formation creeps partially closed, but is propped open by the sand-like material.

After the repository is decommissioned, moisture in the waste or brine from the host rock allows microbiological activity and corrosion to occur, generating gas. Depending on rate of gas generation, amount of brine inflow, and rate of room closure, sufficient gas could be produced to fill available pore space within rooms and drifts. Gas pressure could reach or exceed lithostatic pressure, forcing gas into MB139, anhydrite layers A and B, and the disturbed rock zone (DRZ), desaturating these zones. This gas could vent through an intruding borehole, thereby allowing the repository to resaturate. During drilling, radionuclides are released directly to the surface as the drill penetrates a room or drift and intersects drums or boxes of waste. The waste that is ground up by the drill bit is transported to the surface by circulating drilling fluid. Additional material may be dislodged from walls of the borehole by the circulating fluid as drilling proceeds below the repository (Marietta et al., 1989).

After drilling is completed, the hole is plugged. Because hydrostatic pressure in the Culebra Dolomite Member is less than hydrostatic pressure at the depth of the repository horizon, the connection between the repository and the Culebra Dolomite provides a potential pathway by which the pressures can equilibrate at the lower (Culebra) pressure. This process forces water from the repository and nearby members (Figure IV-4) into the Culebra Dolomite Member. After the pressure within the repository is sufficiently reduced, brine flows in from the host rock as long as pore pressure within the host rock is greater than hydrostatic. This inflow forces brine up the borehole toward the Culebra Dolomite. The borehole plug for this scenario is

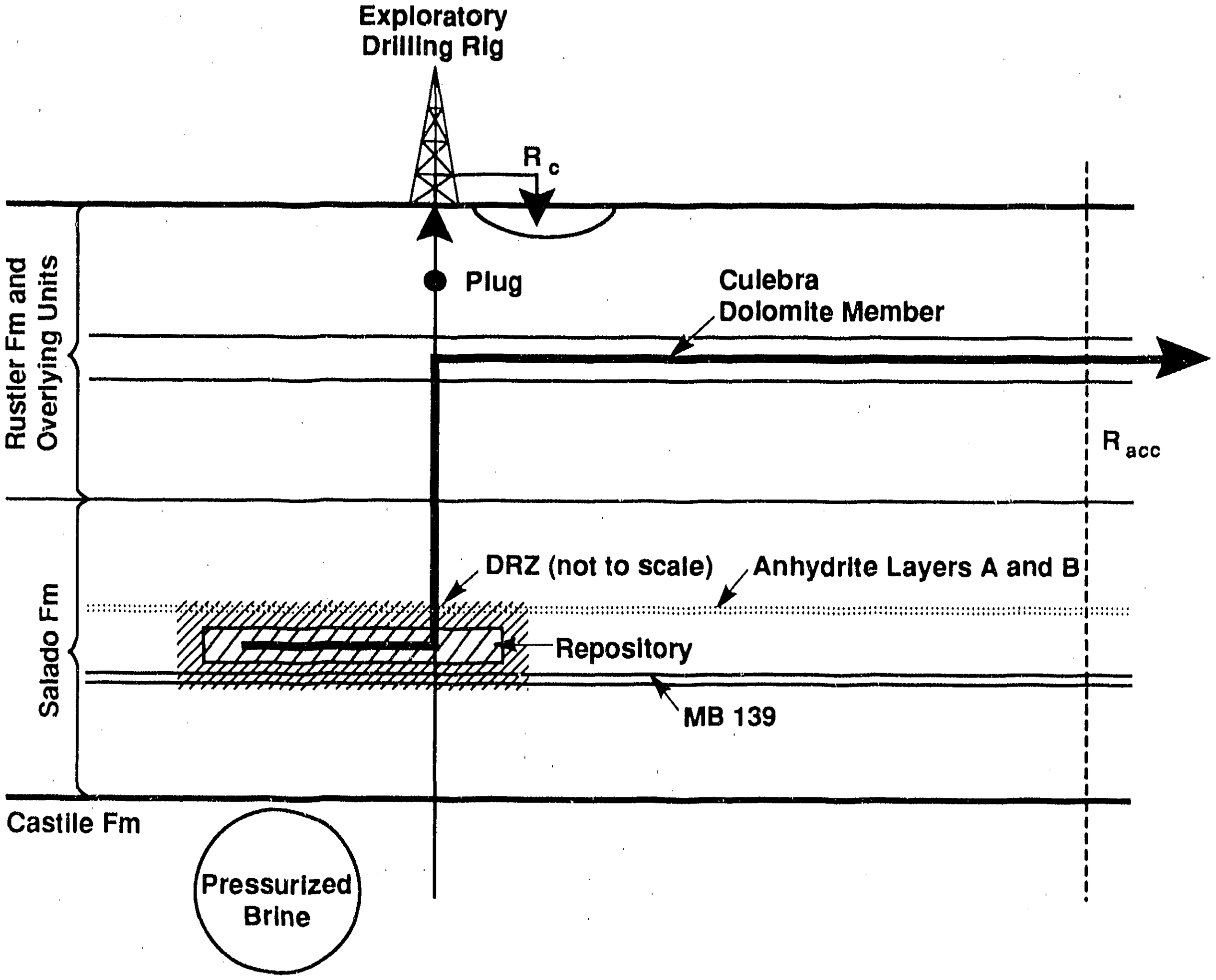


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Figure IV-4. Conceptual Model for Scenario E2. Arrows indicate assumed direction of flow. Exploratory borehole does not penetrate pressurized brine below the repository horizon. R_c is the release of cuttings and eroded material. R_{acc} is the release at the subsurface boundary of the accessible environment. A plug above the Culebra Dolomite Member is assumed to remain intact for 10,000 years.

located so that all flow up the borehole is diverted into the Culebra Dolomite Member. For the analysis of this scenario, it is assumed that the borehole plug does not degrade. Other analyses assumed that borehole plugs degraded in 150 years (Lappin et al., 1989; Marietta et al., 1989).

Intrusion Borehole Through a Room or Drift into Pressurized Brine in the Castile Formation (Scenario E1)

Scenario E1 (Figure IV-5) consists of a single borehole that penetrates through a waste-filled room or drift and continues into or through a pressurized brine reservoir in the Castile Formation in which brine pressure is between hydrostatic and lithostatic for that depth. The borehole is plugged at a level above the Culebra Dolomite Member (Marietta et al., 1989).

A borehole that penetrates a room or a drift intersects containers of waste. This waste is incorporated into the drilling fluid and circulated directly to the mud pits at the surface. After the hole is plugged and abandoned, the brine pressure is assumed to be sufficient to drive flow up the borehole into the Culebra Dolomite Member. As in the E2 scenario, the borehole plug is assumed to be above the Culebra Dolomite and to remain intact, diverting all flow into the Culebra. The flow rate depends on the pressure difference between the Culebra Dolomite and the injected brine and on the hydraulic properties of materials in the borehole. Radionuclides from the room or drift are incorporated into the brine as the brine circulates through the waste adjacent to the borehole. Upon reaching the Culebra Dolomite, the waste-bearing brine flows down the hydraulic gradient toward the accessible environment boundary; this pressurized brine injection results in temporary alterations of the flow field and chemistry in the Culebra Dolomite. Brine flow reduces the local residual pressure in the Castile Formation, thereby reducing the driving pressure of the flow. Eventually, brine stops flowing (Marietta et al., 1989).

Intrusion Borehole Through a Room or Drift into Pressurized Brine in the Castile Formation and Another Intrusion Borehole into the Same Panel (Scenario E1E2)

Scenario E1E2 consists of two boreholes that penetrate waste-filled rooms or drifts in the same panel (Figure IV-6). One borehole also penetrates pressurized brine in the Castile Formation, whereas the other borehole does not. The borehole that penetrates the pressurized brine is plugged between the room or drift and the Culebra Dolomite Member. This plug is assumed not to degrade, forcing into the room all the brine flowing up the borehole. The other borehole is plugged above the Culebra Dolomite Member. This plug is also assumed not to degrade, forcing into the Culebra Dolomite all the brine

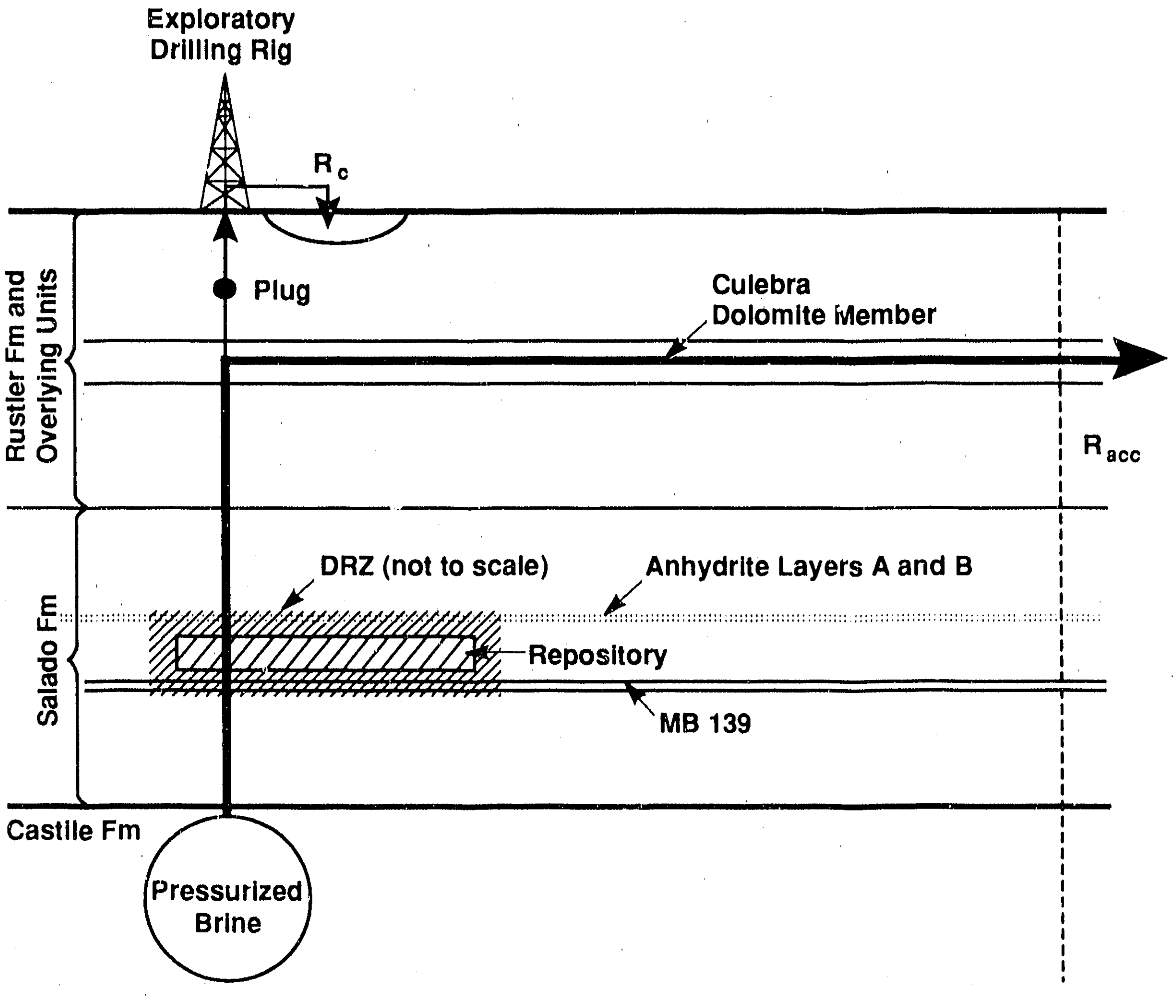

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Figure IV-5. Conceptual Model for Scenario E1. Arrows indicate assumed direction of flow. Exploratory borehole penetrates pressurized brine below the repository horizon. R_c is the release of cuttings and eroded material. R_{acc} is the release at the subsurface boundary of the accessible environment. A plug above the Culebra Dolomite Member is assumed to remain intact for 10,000 years.

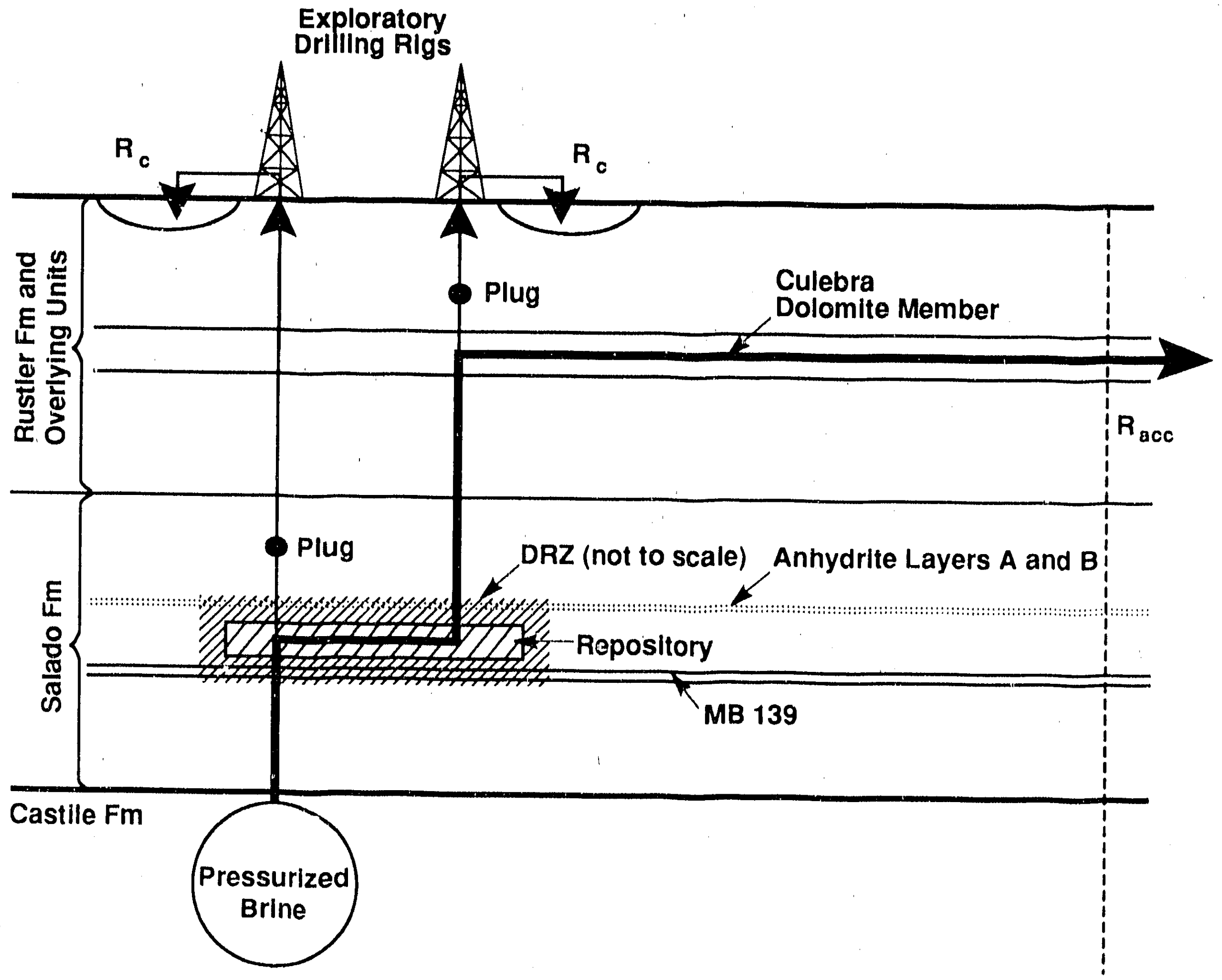

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Figure IV-6. Conceptual Model for Scenario E1E2. Arrows indicate assumed direction of flow. One exploratory borehole penetrates pressurized brine below the repository horizon and a plug between the repository and the Culebra Dolomite Member is assumed to remain intact for 10,000 years. The second borehole does not penetrate pressurized brine below the repository, and a plug above the Culebra Dolomite Member is assumed to remain intact for 10,000 years. R_C is the release of cuttings and eroded material. R_{acc} is the release at the subsurface boundary of the accessible environment.

flowing up this borehole. The brine is assumed to be under a greater pressure than gas or fluid in rooms and drifts of the repository (Marietta et al., 1989).

Radionuclides are released directly to the surface during drilling of the two holes that penetrate the waste-filled rooms or drifts. The radionuclides are incorporated into the drilling fluid and carried to the surface. Additional releases from this system are dependent on the sequence in which the holes are drilled. The plug in the borehole that penetrates the pressurized brine reservoir allows brine flowing up the hole to enter the repository but not leave the repository until the second hole penetrates the same panel. Once the second hole is drilled, a pathway is formed for brine from the pressurized brine reservoir to flow through rooms or drifts, or both, to this new hole and up to the Culebra Dolomite Member. Flow in the Culebra Dolomite is downgradient (Marietta et al., 1989).

If the hole that does not penetrate pressurized brine is drilled first, gas and/or fluid pressure is relieved; this is followed by groundwater flow and radionuclide transport up the hole as a result of brine inflow into the panel from the host rock, possibly enhanced by creep closure of rooms and drifts. Flow is diverted into the Culebra Dolomite Member by the plug located above this unit. The subsequent drilling and plugging of the borehole that penetrates the pressurized brine reservoir results in flow through the repository and up the other borehole. After the driving pressure is depleted, Scenario E1E2 reverts to Scenario E2, because the borehole that penetrates the pressurized brine no longer contributes to flow and transport (Marietta et al., 1989). Analyses of Scenario E1E2 assume that both boreholes are drilled at or close to the same time for modeling convenience.

The sequence of drilling, time lapsed between drilling events, and distance between the two boreholes in the same panel all affect radionuclide migration. Flow through the rooms and drifts depends on the hydraulic properties of the waste backfill, and seals placed in these openings and on the pressure gradient between the holes. For some configurations, flow from one hole to the other may take longer than the regulatory period or take sufficiently long to allow significant decay of radionuclides in transport. These issues are addressed in the analyses described under "Multiple Intrusion Events."

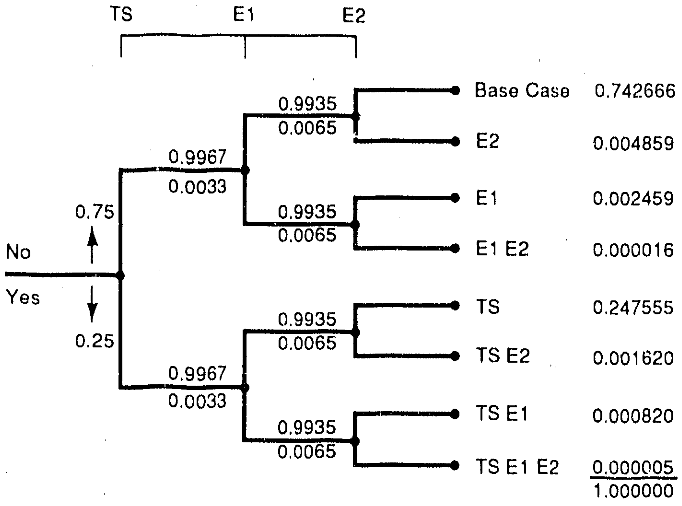
Scenario Probability Assignments

For this preliminary performance assessment, scenario probabilities must be assigned so a final mean CCDF can be constructed from the eight scenarios shown in Figure IV-2. These probabilities were estimated for the methodology demonstration (Marietta et al., 1989). These estimates were called weights to emphasize that they were only preliminary. Possible approaches to determining probabilities of occurrence for the above events were reviewed and additional probabilities were estimated by Guzowski (in prep.), who concluded that probability assignments for the compliance assessment should rely on expert judgment. A formal expert-judgment elicitation (e.g., Bonano et al., 1989; also see Ch. VIII) has begun. This elicitation focuses on identifying a set of mutually exclusive futures, modes of intrusion for each future, and frequencies of intrusion for each mode. The effects of possible markers and barriers will be considered through additional expert-judgment elicitations. Because the elicitation of expert judgments is not complete, preliminary probability estimates also must be used for this assessment.

Preliminary probability estimates are based on the current understanding of natural resources in the vicinity of the repository, projections of future drilling activity, and regulatory guidance. Guzowski prepared the two sets of probability estimates (Marietta et al., 1989; Guzowski, in prep.) that are compared here. Neither set is considered credible enough to be used as final probability estimates in the absence of formal expert-judgment elicitation (Guzowski, in prep.). Both sets of preliminary probabilities, derived by using different probability techniques, are used in this preliminary assessment, and the resultant comparison of simulated performances provides a measure of the sensitivity of the modeling system to the uncertainty in scenario probability assignment. One set, primarily using a classical-model approach based on the theory of indifference (Weatherford, 1982), contains estimates for event probabilities of 0.0065 for drilling into a room or drift (E2), 0.0033 for drilling into a room or drift and penetrating a pressurized brine occurrence (E1), and 0.25 for subsidence due to potash mining outside the controlled area (TS) (Guzowski, in prep). The scenario probabilities can be estimated from the logic diagram as before (Figure IV-7). The second set (Marietta et al., 1989) contains estimates for event probabilities of 0.17 for E2, 0.085 for E1, and 0.05 for TS and yields a much different set of scenario probabilities (Figure IV-8). The probability of human intrusion is 0.01 for the first set and 0.24 for the second set.

MULTIPLE INTRUSION EVENTS

The possibility of multiple intrusion boreholes through the waste panels over 10,000 years requires changes in the two-borehole modeling approach to facilitate the calculational process. First, the distribution of pressurized brine reservoirs will be treated as features within the conceptual model. The map (Earth Technology Corporation, 1988) of this feature identifies the area of the waste panels where a borehole could penetrate both a waste panel and pressurized Castile brine (Figure IV-5). Spatial distribution of the intrusion event now becomes an uncertain input parameter to be sampled. For each intrusion event, the location within the waste panels determines the



TS - Subsidence Resulting from Solution Mining of Potash
E1 - Drilling through Room and Brine Pocket
E2 - Drilling through or into a Room

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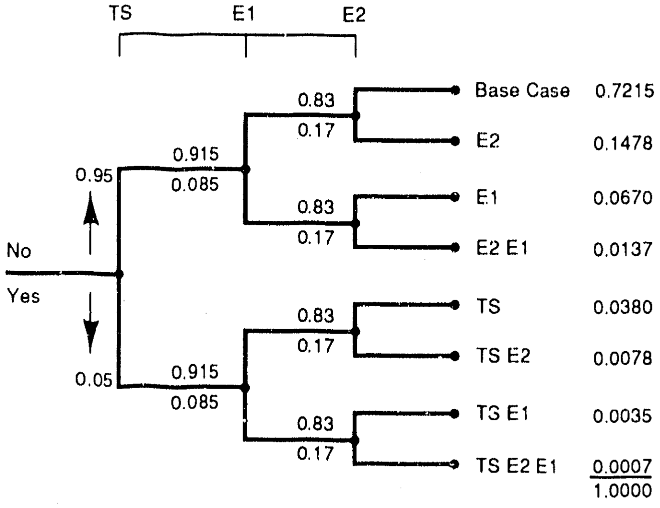
Figure IV-7. Scenario Probability Estimate Based on Guzowski, in prep.



TS - Subsidence Resulting from Solution Mining of Potash
E1 - Drilling through Room and Brine Pocket
E2 - Drilling through or into a Room

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Figure IV-8. Scenario Probability Estimate Based on Marietta et al., 1989.

type of event (E1 or E2). Because all potential hydrocarbon pay zones are below the Castile Formation, all exploratory boreholes are assumed to be drilled to target horizons below the Castile; therefore there is no reason to sample on depth.

Second, pending guidance from the expert-judgment elicitation, the regulatory upper-bound penetration rate of 15 boreholes/10,000 years is assumed for the one-half km^2 waste panel area. Each simulation of a human intrusion scenario includes between one and fifteen intrusion events. Selecting the timing and number of events is part of the uncertainty analysis. In this way, the calculation of releases can proceed from event to event with the type of calculation (E1, E2, E1E2, etc.) determined by the sampled location within the waste panels and its relation to previous events. With this approach, the logic diagram is further simplified to just two levels, TS and E (Figure IV-9), where E designates a variable number of boreholes through waste-filled rooms or drifts. The arbitrary assumptions used to define the E1E2 scenario are abandoned. Two intrusions need not occur simultaneously, nor are borehole plugs necessarily assumed to direct all flow from the Castile brine reservoir through the repository. Plugs between the Culebra Dolomite and the surface are assumed to remain intact, diverting all flow into the Culebra.

A Poisson distribution is used to represent the number of events that occur over equal intervals of time assuming that events occur independently at a constant average rate. In the absence of regulatory or expert guidance, this probability model is assumed for human intrusion by exploratory drilling as an example model for judging the effect of multiple intrusions on predicted repository performance (Tierney, in prep.).

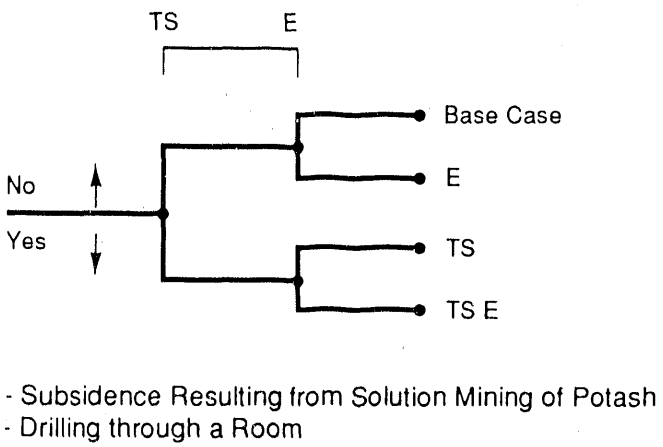

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Figure IV-9. Simplified Logic Diagram

V. COMPLIANCE ASSESSMENT SYSTEM

The text of Chapter V is preceded by a synopsis that simplifies concepts presented in Chapter V. Detailed information about those concepts is in the text following the synopsis.

Synopsis

The WIPP compliance assessment system contains the procedures and modeling tools necessary to model consequences and analyze parameter uncertainty and sensitivity for the selected scenarios.

The Standard requires that disposal systems incorporate both natural and man-made barriers to migration of radionuclides.

Natural Barrier System

Natural barriers in the WIPP disposal system are the hydrogeology and geochemistry of the controlled area.

Hydrogeology

The important water-bearing rock units for regional groundwater flow in the vicinity of the WIPP are, in ascending order, the Rustler-Salado residuum and the Culebra and Magenta Dolomite Members of the Rustler Formation.

Rustler-Salado Residuum

The Rustler-Salado residuum is the first water-bearing unit above the Salado Formation, the host rock for the WIPP, and consists of residue from the dissolution of upper Salado and lower Rustler Formation salt.

Hydraulic conductivity, a factor controlling fluid flow through the rocks, is low in the vicinity of the WIPP, and increases west and northwest of the WIPP, toward Nash Draw.

The unit is confined between two extremely low permeability layers over most of the area but is unconfined in the vicinity of Malaga Bend southwest of the WIPP.

The residuum gains water north of the WIPP and discharges it to the southwest.

Culebra Dolomite Member of the Rustler Formation

The Culebra Dolomite Member is a microcrystalline dolomite about 8 meters (26 feet) thick, and is present throughout the WIPP area.

The Culebra is confined between two low-permeability layers in the vicinity of the WIPP but is unconfined near Malaga Bend at the lower end of Nash Draw.

Hydraulic conductivity is low east of the WIPP, and increases to the west in Nash Draw and near Malaga Bend.

The Culebra gains water north and east of the WIPP and discharges it to the southwest.

Magenta Dolomite Member of the Rustler Formation

The Magenta Dolomite Member is similar in composition and thickness to the Culebra Dolomite Member but is not present west of the WIPP in Nash Draw.

The Magenta gains water from the north and possibly east and discharges it through fractures into the Culebra Dolomite Member.

Supra-Rustler Units

The units above the Rustler are considered as one water-bearing unit. The unit contains little water except for some locally unconfined sands that provide water for a few livestock wells. The supra-Rustler units probably gain water directly from precipitation.

A 3-meter (10-feet) thick unit of caliche that is present throughout the area inhibits downward flow to the Rustler Formation.

Long-Term Climate Variability

Changes in the climate of southeastern New Mexico during the next 10,000 years may affect repository performance.

In particular, changes in the average level of precipitation could affect water gain to the Rustler Formation and the currently unsaturated overlying units.

A fundamental assumption is that climatic extremes of the next 10,000 years will not exceed those associated with glaciations and deglaciations that have occurred repeatedly in the northern hemisphere since approximately 2.5 million years ago.

As presently understood, climatic changes caused by human activities will not exceed glacial extremes.

Past Variations in Global Climate

Long-term stability of the cycles of glaciation and deglaciation during the last 2.5 million years provides the basis for concluding that climatic extremes of the next 10,000 years will remain within past limits.

According to the pattern, the next maximum glaciation will not occur for many tens of thousands of years.

Past Precipitation Record at the WIPP

Three significant conclusions about precipitation can be drawn from the climatic record of the American Southwest:

> Maximum precipitation in the past coincided with the maximum advance of the North American ice sheet; minimum precipitation occurred after the ice sheet had retreated to its present limits.
>
> Past long-term average precipitation levels were, at a maximum, roughly twice the present levels; minimum levels may have been slightly less than present levels.
>
> Short-term fluctuations in precipitation have occurred during the present, relatively dry, interglacial period; however, they have not exceeded the upper limits of the glacial maximum advances.

A direct extrapolation of the precipitation curve into the future is unrealistic. At present, predicting the probability of a recurrence of a wetter climate such as that of approximately 1,000 years ago is not possible.

The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of about 18,000 to 20,000 years ago.

Radionuclide Transport in the Culebra

The Culebra Dolomite Member of the Rustler Formation is the first significant, laterally continuous, water-bearing unit above the WIPP repository.

The Culebra has been identified as one of the most important paths for transport of radionuclides from the repository to the accessible environment.

Given the fractured nature of the Culebra, three possible conceptual models for transport are a discrete-fracture model, a porous-flow model, and a dual-porosity model.

Analysis of well tests indicates that the dual-porosity model is most consistent with local observational data for the Culebra.

Geochemistry

Retardation of radionuclides during groundwater transport in the Culebra Dolomite Member of the Rustler Formation provides a potential geochemical barrier between the repository and the accessible environment.

Retardation, the removal from solution or delay of radionuclides during transport, is a complex function of water chemistry, rock chemistry, and the geometry of the flow path.

The Culebra Dolomite Member

Based on available well data, four zones of differing chemical composition have been recognized in Culebra Dolomite Member groundwater.

The differing chemical zones are not distributed consistently with the observed north-to-south flow of groundwater in the Culebra Dolomite. Less saline waters are down-gradient from more saline waters.

Direct recharge of fresh water could account for the characteristics of the less saline groundwater.

A different theory is that all Culebra Dolomite waters, including those in the less saline zone, are between 12,000 and 16,000 years old; past groundwater flow may have been from west to east, rather than north to south. Present flow could be transient, reflecting gradual drainage of the system. Regional chemical zones may reflect geographic distribution of halite during a past flow regime.

On a more local scale, within zones near the repository, water chemistry may be in partial equilibrium with the modern flow regime.

Retardation of Radionuclides in the Culebra

Distribution coefficients (K_ds) are used in simulations of transport to calculate retardation caused by the partitioning of radionuclides between groundwater and rock.

K_ds can be determined experimentally for different kinds of radionuclides, but direct extrapolations of experimental data to a complex natural system are of uncertain validity.

Retardation of radionuclides can also be a function of the distribution of minerals such as dolomite, gypsum, and clays within the pore spaces.

Results of present experimental and theoretical research indicate that retardation of uranium and plutonium by clay minerals could be substantial.

Evidence indicates that some clay minerals will take up and hold dissolved uranium and uranyl-carbonate and uranyl-EDTA complexes, which could be present in brine contaminated by radionuclides from rooms in the WIPP.

Preliminary information suggests that retardation factors are orders of magnitude higher than those used in earlier simulations.

Calibrating Groundwater Flow Models for the Culebra

Groundwater flow models for the Culebra Dolomite Member must provide adequate confidence for predicting flow and transport over 10,000 years.

Calibration estimates parameter values to obtain acceptable agreement between computed and measured past behavior of the groundwater-flow system.

Existing Calibrated Fields

An extensive steady-state and transient calibration exercise for the WIPP included 10 years of data acquisition, interpretation, and simulation of the Culebra Dolomite Member.

Performance Assessment Approach

The objective for the final performance assessment is to simulate flow and transport in a way that displays the residual parameter and conceptual model uncertainty when all available observational information is taken into account.

An interim approach employing zones of constant hydrologic properties has been used for this preliminary performance assessment.

Repository/Shaft System

The repository/shaft portion of the compliance assessment modeling system describes flow and transport within the underground workings at the repository horizon and within various shafts and boreholes that connect the underground workings with the overlying formations.

For the undisturbed scenario, the modeling problem is to predict transport of radionuclides from the rooms through the entire repository/shaft system to overlying fluid-bearing rock units.

For disturbed scenarios, an intrusion borehole that penetrates a storage room serves as the only flow connection with overlying or underlying formations.

CAMCON provides an efficient, readily available tool for linking models of components within the repository/shaft system.

The component of the repository/shaft system model that describes a single room incorporates many properties and phenomena, such as:

Creep closure of the salt
Brine inflow from the Salado Formation
Structural response of the backfill mix
Structural response of the waste containers and contents
Inventory and waste categories
Room and brine chemistry
Gases generated by microbiological, radiolytic, and corrosive decomposition of waste and containers
Brine and gas interactions with the backfill mix
Gas interactions with the Salado Formation
Brine and gas interaction with MB139 and overlying anhydrite layers
Solubilities of the radionuclides in the room environment
Effect of intruding drilling fluids
Effect of injected pressurized brines from intrusion boreholes

For the undisturbed scenario, transport through panel seals, the MB139 seal, and shaft seals must be modeled.

The assembly of these components into a systems model requires individual component and system sensitivity analyses to identify important parameters and processes.

Waste Panel Modeling

The disposal-room characterization program studies how radioactive waste and backfill mixtures interact in a waste room as the mixture consolidates in response to creep deformation of the surrounding salt.

For the WIPP performance assessment, a major requirement is that room modeling describe not only the state of the room when an intrusion event occurs, but also the transient response following that event so that the migration of radionuclides away from the room can be predicted.

All processes are linked, and all are rate- and time-dependent.

Responses of the disposal system to human intrusion depend on the time of intrusion, the degree to which the repository has closed by salt creep, and the amount of gas generated.

Models and the data base needed to describe detailed conditions within the waste-disposal area are still being developed. Current interpretations are based on simplified assumptions that will be modified as research progresses.

The Source of Radionuclides

Current performance assessment calculations use an initial waste inventory that includes both contact-handled and remotely handled waste.

Because remotely handled canisters will occupy only a very small area of the repository, current simulations of direct removal of waste to the ground surface by drilling use only the contact-handled waste inventory.

The importance of lower probability intrusions directly through the remotely handled waste will be examined in future performance assessments.

Transport calculations do not consider gaseous transport of volatile radionuclides, because the maximum activity of the only radioactive gas expected in the repository is insignificantly small over 10,000 years.

Panel-Seal Modeling

Panel seals isolate disposal rooms from the remainder of the repository.

Models within the panel-seal module include:

Seal-material consolidation
Brine inflow and gas outflow
Disturbed rock zone
Flow and transport
Panel seal and room assemblage

Passageway Modeling

A module within CAMCON will simulate flow and transport from the northernmost panel seals to the concrete bases of the shafts.

Shaft-Seal System

The four shafts will have multi-component seals extending from the passageways upward to the surface. Each shaft-seal system will consist of an upper seal and a lower seal.

The upper seals have a temporary function of limiting seepage of Rustler Formation brine into the lower system until the lower seals consolidate.

The lower seals will contain crushed salt that will consolidate as the host rock creeps laterally into the shaft.

Additional models that have been developed or are under consideration are:

Seal-material consolidation
Brine inflow and gas outflow
Disturbed rock zone
Flow and transport
shaft-seal system

Release Mechanisms

Future exploration for natural resources could result in the breaching of the repository by a borehole.

Intrusion through Upper Units into Waste Panels

In an intrusion, some waste material will be brought directly to the ground surface during the drilling operation. This material will be released to the accessible environment in a settling pit at the surface.

The amount of waste removed as cuttings is a simple function of the diameter of the drill bit.

Estimating the amount of waste removed as cavings, the material eroded from the borehole, requires a more complex conceptual model. Variables controlling erosion by flowing fluid include the drilling speed, the fluid circulation rate, the diameter of the drill bit, fluid viscosity, fluid density, borehole roughness, and the rock composition.

Intrusion through the Castile Formation

Pressurized brine has been found in fractured anhydrite of the Castile Formation below the repository.

Previous calculations ignored the possibility of gas-driven flow, but one test well has produced some gas; gas in an intruding borehole could enhance flow through the borehole.

Dual-porosity flow that includes gas has not been explicitly included in flow calculations for a Castile pressurized brine reservoir; however, the assigned range of uncertainty in data from the test well accounts for the effect of dual-porosity flow in the long-term predictions.

Intrusion through the Bell Canyon Formation and Deeper Units

Intrusion would create a potential pathway for fluid migration between the Culebra Dolomite Member of the Rustler Formation above the repository, the repository itself, and the Bell Canyon Formation and deeper units.

Relatively little is known about the mechanism that would drive flow along this pathway, but data from five wells drilled into the Bell Canyon Formation suggest that flow would be slight, and, in a borehole without pipe down its entire length, downward.

Well data indicate that upward flow of fluid from the Bell Canyon Formation is unlikely to contribute to radionuclide releases.

Preliminary simulations do not consider consequences of intrusion into units below the Castile Formation.

Human Exposure

To evaluate potential human exposure and compliance with the Individual Protection Requirements, concentrations of radionuclides as a function of space and time must be calculated.

Undisturbed conditions of the repository are used for these calculations.

An "exposure pathway" is a potential route through which humans may be exposed to radionuclides or radiation. A specific pathway describes the route of exposure such as a contaminated-water-to-beef-to-man ingestion pathway.

Only pathways that arise from withdrawal wells to aquifers with potable water for cattle consumption will be considered for compliance with the Individual Protection Requirements.

If releases to the accessible environment are predicted, necessitating human dose calculations, uncertainty in published values for dose equivalents will have to be included.

CAMCON

Simulating the complex disposal system at the WIPP requires that computer programs in the compliance assessment system be controlled by an executive program (CAMCON).

An executive program must:

Link distinct model components with little analyst intervention.

Identify and trace calculations to insure repeatability and avoid misinterpretation.

Control statistical sampling simulations.

Allow easy examination of intermediate diagnostics and final results.

Provide easy replacement of component programs within the executive program.

Primary Data Base

The primary data base contains measured field and laboratory data gathered during the disposal-system and regional characterization.

Secondary Data Base

The secondary data base contains interpreted data and incorporates the information that comprises the conceptual model of the disposal system.

Computational Data Base

The computational data base containing the results of calculations made by components of CAMCON is called "Compliance Assessment Methodology Data" (CAMDAT).

Program and Model Applications

The **SUTRA** computer program predicts brine flow into a waste panel.

The **PANEL** computer program estimates discharge of brine and radionuclides from a borehole to the Culebra Dolomite Member of the Rustler Formation.

The **SECO2D** computer program simulates two-dimensional groundwater flow.

The **CTAFF2D** computer program, a two-dimensional finite element program, simulates groundwater and solute transport in fractured or granular aquifers.

The **BOAST II** computer program, a petroleum reservoir model, simulates two-phase flow in a three-dimensional, porous medium.

The **BRAGFLO** computer program simulates transient two-phase flow of brine and gas in a porous reservoir.

The **NEFTRAN** computer program simulates transport of radionuclides through a porous or fractured medium.

Monte Carlo Simulation Techniques

Parameters used for models in the WIPP performance assessment are uncertain because:

Measurement techniques may be either incorrect or misapplied.

Parameter values are based on statistical reductions of measured data.

Variable parameters are replaced with lumped parameters.

Random variations are replaced with deterministic parameters.

Data may be misinterpreted.

Natural variations exist within the system.

Because of this unavoidable uncertainty, parameter values must be assigned by statistically sampling a range of values. Multiple Monte-Carlo simulations are performed using different samples of parameter values.

The WIPP compliance assessment system contains the procedures and modeling tools necessary to model radionuclide migration from the repository and analyze parameter uncertainty and sensitivity for the selected scenarios. This chapter describes the scenario conceptual models and computer programs that comprise the modules of the system used for consequence modeling and the statistical techniques used for uncertainty and sensitivity analyses. The components of the compliance assessment system are shown in Figure III-2. These components are described in more detail in the following sections.

Some of the discussion in the sections describing the repository and shaft subsystems is speculative, because data and understanding have not advanced far enough to confirm hypothesized behavior or to confirm component designs. Extensive work (Bertram-Howery and Hunter, 1989a; U.S. DOE, 1990a) is continuing, so the discussion of this work and the supporting documentation will likely change before the final *Comparison* is prepared.

Natural Barrier System

The geologic setting of the WIPP provides significant natural barriers to radionuclide migration. Groundwater flow, which provides the primary pathway for radionuclide migration from any geologic repository, is essentially nonexistent in the host Salado Formation, and is limited in overlying units. If radionuclides reach overlying water-bearing units, specifically the Culebra Dolomite Member of the Rustler Formation, geochemical retardation during transport will provide an additional barrier to migration.

HYDROGEOLOGY

Understanding the hydrogeology of the Los Medaños region is fundamental to performance assessment. Travel time, possible flow paths, and radionuclide retardation depend on the regional geology and hydrology. The stratigraphy and hydrostratigraphic units important to modeling regional groundwater flow in the northern Delaware Basin and summarized in this section are from Brinster (in prep.).

The Los Medaños Study Area is in the north-central part of the Delaware Basin, which is in the southern part of the Pecos Valley of the Great Plains physiographic province. The province lies between the high plains of west Texas and the Guadalupe and Sacramento Mountains of southeastern New Mexico. The Study Area is 40 by 40 km (25 by 25 mi) and extends from the Pecos River in southern Eddy County eastward into Lea County and southward from just inside the Delaware Basin to about 20 km (12 mi) north of the New Mexico-Texas state line (Figure V-1). The Study Area includes four prominent surface features: Nash Draw, Laguna Grande de la Sal, The Dunes (Los Medaños) and the Pecos River. These features are described in Chapter I (see "Physical Setting").

Guadalupian Hydrostratigraphic Units

The Guadalupian hydrostratigraphic units of interest in the Delaware Basin consist of the Bell Canyon Formation (basinal unit) and the Capitan Limestone (reef unit) (Figure V-2). The back-reef units are not considered in this study. The massive Capitan Limestone ranges in thickness from 76 to 230 m (250 to 750 ft) and averages 120 m (390 ft). Hydraulic conductivity ranges from 8×10^{-6} to 9×10^{-5} m/s. Effective porosity, which is enhanced by dissolution and fracturing of the limestone, is about 0.08. Groundwater flows from the Guadalupe Mountain recharge area eastward around the periphery of the Delaware Basin, into the shelf aquifer toward Texas. Groundwater-flow direction is influenced locally by the Pecos River and by large withdrawals resulting from oil and gas drilling activity. Fluid density ranges from 1.000 to 1.115 g/cm^3 and averages about 1.04 g/cm^3 (Hiss, 1975; Mercer, 1983).

The lowest basinal hydrostratigraphic unit and oldest unit to outcrop in the northern Delaware Basin, the Bell Canyon Formation, is the fore-reef equivalent of the Capitan Limestone and interfingers with the Capitan at the basin margins. The upper part of the Bell Canyon is composed of informally named sandstone and shale members, which are, in ascending order, the Hays sandstone, Olds sandstone, Ford shale, Ramsey sandstone, and Lamar limestone (Brinster, in prep.). The upper siltstones and shales contain elongated sandstone stringers that were deposited by density currents moving along the bottom, basinward from the reef (Figure V-3). Groundwater occurs in the upper portion of the unit (Williamson, 1978; Hiss, 1976; Harms and

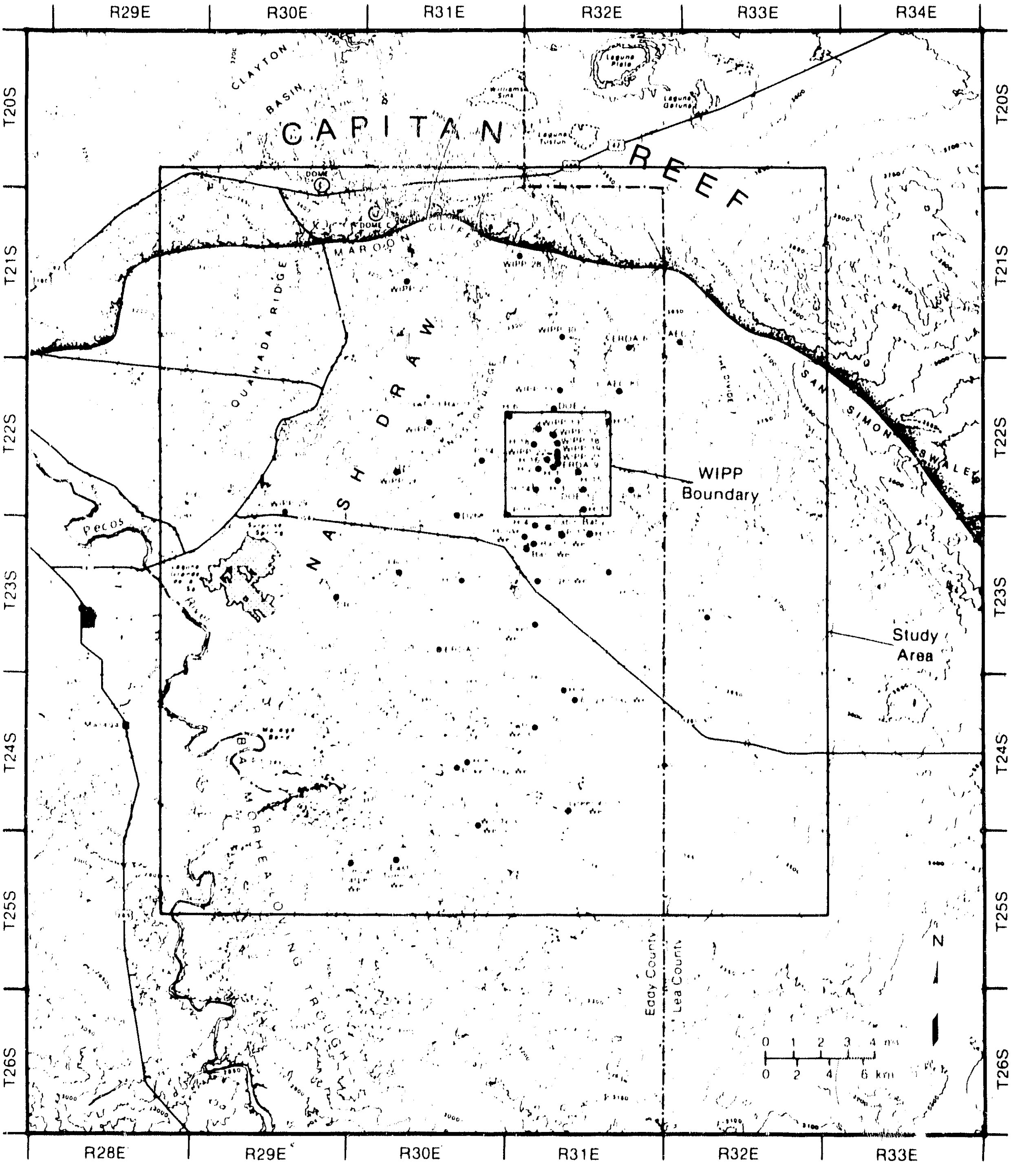

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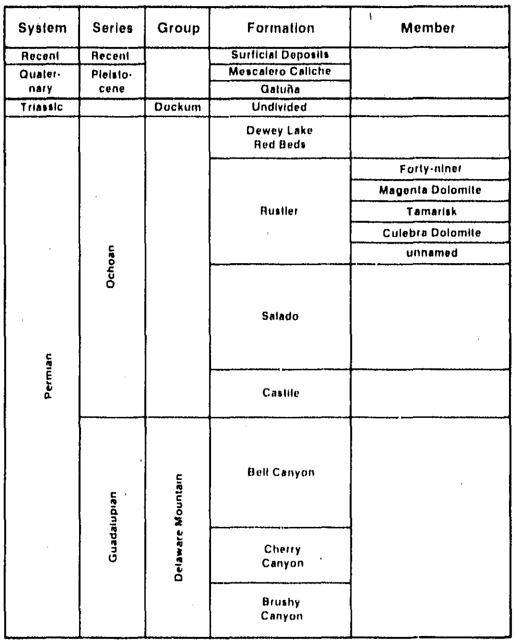
Figure V-1. Map of the Los Medaños Study Area Showing the Boundaries of the Study Area (Brinster, in prep.), the Proposed Land Withdrawal, and the Observation Well Network (Haug et al., 1987).



System	Series	Group	Formation	Member
Recent	Recent		Surficial Deposits	
Quaternary	Pleistocene		Mescalero Caliche	
			Gatuña	
Triassic		Dockum	Undivided	
Permian	Ochoan		Dewey Lake Red Beds	
			Rustler	Forty-niner
				Magenta Dolomite
				Tamarisk
				Culebra Dolomite
				unnamed
			Salado	
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

Figure V-2. Generalized Stratigraphic Column of the Delaware Mountain Group and Younger Sedimentary Rocks of and near the WIPP Disposal System (Beauheim, 1987).

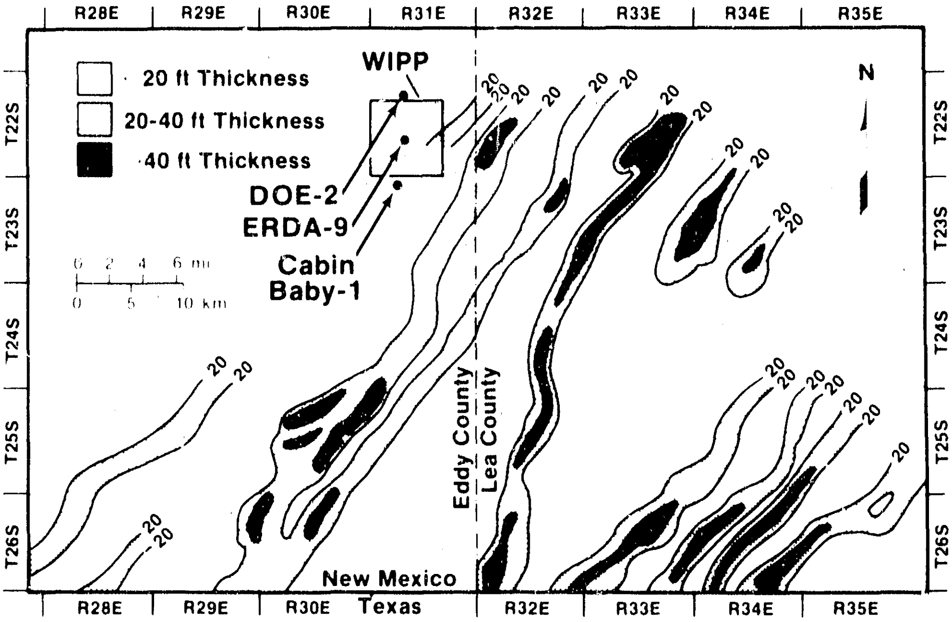


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Figure V-3. Map Showing the Orientation of the Upper Bell Canyon Sandstone Stringers in the Vicinity of the WIPP (modified from Lappin, 1988).

Williamson, 1988; Lappin, 1988). The vertical potential of the freshwater equivalent heads of this unit is upward, leading to the speculation that the Bell Canyon waters have in the past contributed to dissolution of the Castile Formation and caused collapse features that can be seen at the surface (Anderson et al., 1978; Anderson, 1981). The Castile, however, does not have the extensive fracture network necessary for pathways upward to the halites and back down to the Bell Canyon (Lambert, 1983). The Bell Canyon will not be included in the numerical modeling because of the poor hydraulic connection to the upper hydrostratigraphic units and because there is no potential for upward vertical flow; furthermore, any radionuclides reaching the Bell Canyon Formation will not be transported laterally with significant velocity.

Ochoan Hydrostratigraphic Units

Near the end of the Bell Canyon deposition, circulation within the Delaware Basin became more restricted, resulting in a thick sequence of organic layers alternating with siltstone laminations that changes in character upward from organically-layered calcite to calcite-layered anhydrite. This thick sequence forms the lower Castile Formation, which then grades upward into the anhydrite-layered halite of the upper Castile Formation and the thick halite of the Salado Formation (Figure V-2). The Salado Formation is of particular interest because it is the host rock for the WIPP.

The Castile and Salado Formations are present everywhere in the Study Area but are eroded away southwest of the Study Area (Figure V-3). In New Mexico, north of the WIPP, the Castile Formation is about 360 m thick and thickens southward across the WIPP, where it is about 470 m thick. At the southern edge of the Study Area the Castile Formation is about 500 m thick. Throughout the Study Area, the Salado Formation is about 600 m thick and contains bedded salt rhythmically interbedded with anhydrite, polyhalite, glauberite, and some thin mudstones (Adams, 1944; Bachman, 1981; Mercer, 1983). The Salado Formation is deformed slightly by a series of low anticlines and shallow synclines with axes dipping southeastward. In the northeastern part of the Study Area, the Salado Formation surface dips steeply northeastward. Unlike the Castile Formation, the Salado Formation overlaps the reef structure and extends eastward beyond the reef for many kilometers into west Texas and the Texas panhandle.

Conservative estimates of the hydraulic conductivity of the Castile Formation yield a range of about one nanodarcy (1.0×10^{-14} m/s) to about 0.1 microdarcy (1.0×10^{-12} m/s) (Mercer, 1983). Porosity of the anhydrite is about 0.001.

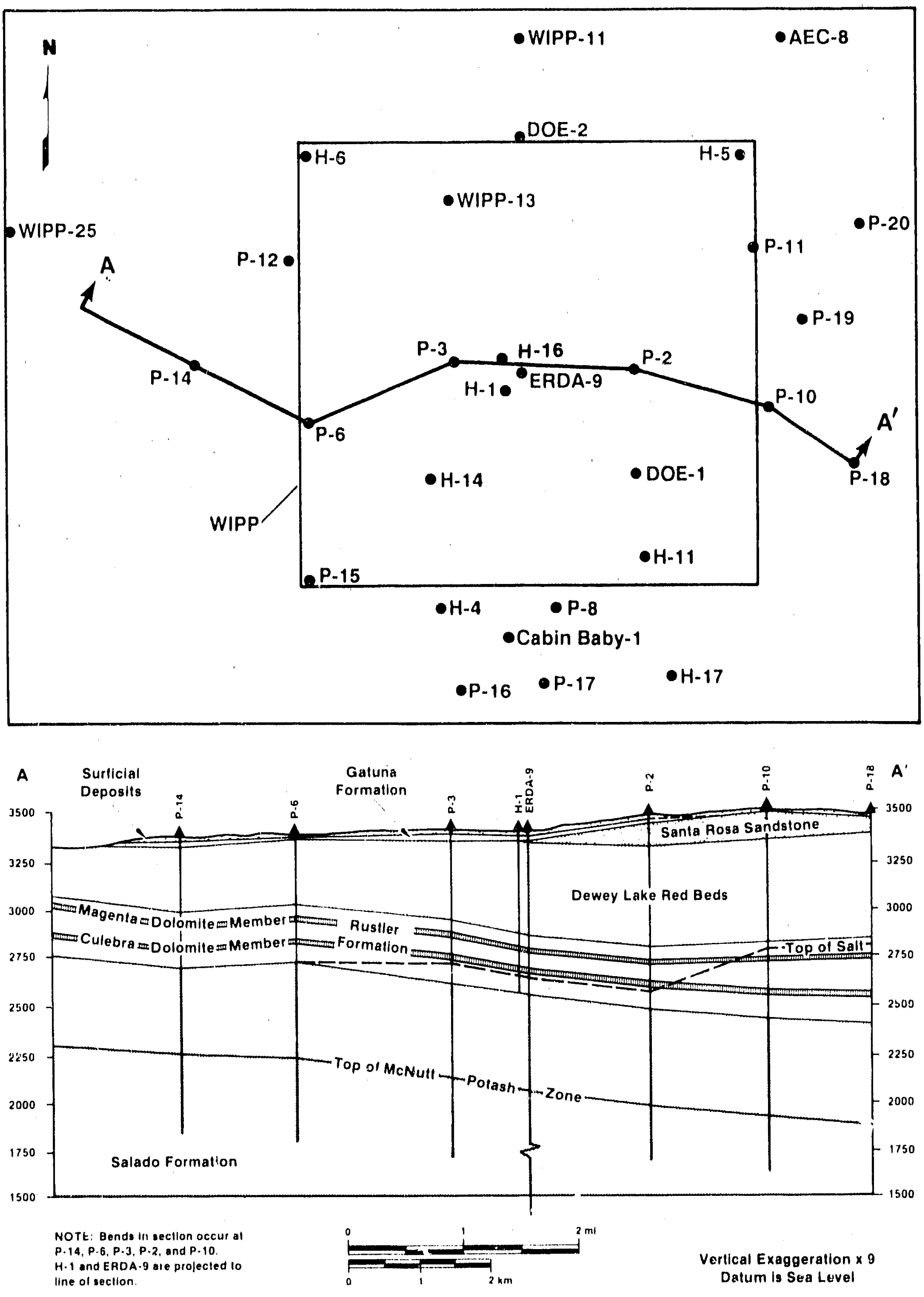
In the Study Area, where the Salado Formation is complete, the volume of groundwater flow is minimal because (as is the nature of highly plastic salt deposits) the salt lacks primary porosity and open fractures. The permeability of the Salado Formation is very low and ranges from 9 nanodarcies (9 x 10^{-21} m^2) to 25 microdarcies (2.5 x 10^{-17} m^2) throughout the formation. Porosity is estimated to be 0.001 (Mercer, 1983, 1987; Powers et al., 1978; Bredehoeft, 1988). Formation pressure varies from hydrostatic to lithostatic and, although the formation may be saturated, it has a very low effective porosity and very little groundwater movement (Mercer, 1987; Mercer et al., 1987)

Hydrogeology of the Rustler Formation

The Salado Formation is conformably overlain by the Rustler Formation, which is the youngest unit of the Ochoan evaporite series (Figures V-2 and V-4). The Rustler Formation is of particular interest because it contains water-bearing units that may provide potential pathways for radionuclides to reach the accessible environment.

The composition of the Rustler Formation is about 40 percent anhydrite, 30 percent halite, 20 percent siltstone and sandstone, and 10 percent anhydritic dolomite (Lambert, 1983). The Rustler is divided into four formally named members and a lower unnamed member on the basis of the lithologies of units that crop out along Nash Draw west of the WIPP (Vine, 1963). The five units (Vine, 1963; Mercer, 1983) are, in ascending order, the lower unnamed member (oldest), the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member (youngest) (Figure V-2).

Groundwater in the Rustler previously was thought to be restricted to the residuum between the Rustler and Salado Formations (termed the Rustler-Salado residuum) and the two dolomite members: the Culebra and Magenta (Vine, 1963; Mercer, 1983). Flow occurs in a siltstone unit of the unnamed lower member, and in claystones of the Tamarisk and Forty-niner Members (Beauheim, 1987; Holt et al., 1989). Claystone in the Tamarisk Member is separated from dolomite in the Culebra and Magenta Members by anhydrite layers. Claystone in the Forty-niner Member is likewise separated from the Magenta Dolomite and the overlying Dewey Lake Red Beds by anhydrite with an extremely low hydraulic conductivity. Data on the unnamed lower member, the Tamarisk Member, and the Forty-niner Member are from two wells: H-14 and H-16 (discussed below) (Figure V-4). Figure V-5 shows the location of wells used to conceptualize groundwater flow near the WIPP.



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3 Figure V-4. Geologic Cross-Section Across the WIPP Disposal System (Mercer, 1983).

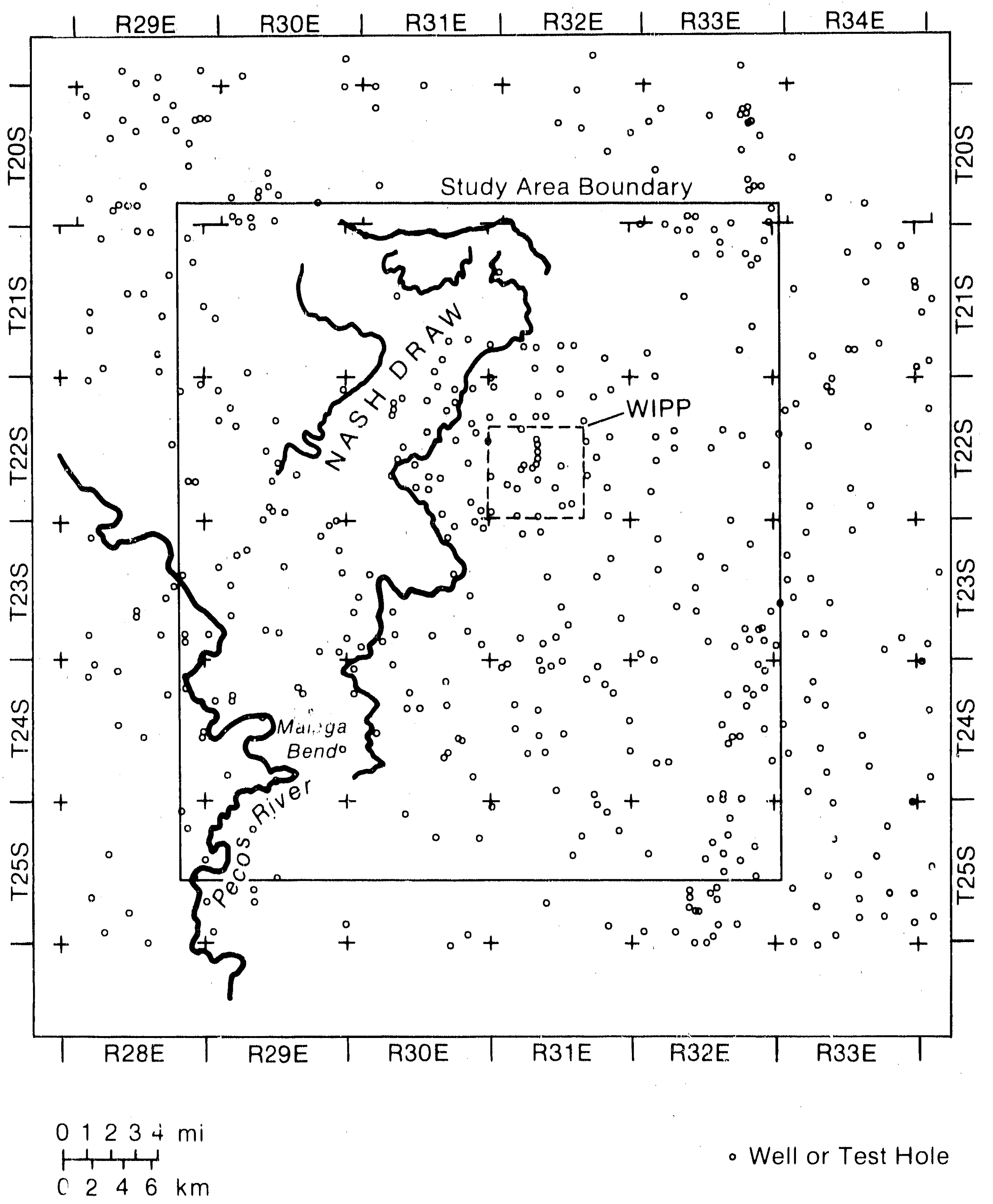

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Figure V-5. Wells in the Vicinity of the WIPP.

Rustler Aquitard Units

The lower unnamed member has a mean thickness of about 40 m (131 ft), is about 36 m (118 ft) thick at the WIPP, and thickens slightly eastward across the Study Area. The unit is composed mostly of fine-grained silty sandstones and siltstones interbedded with anhydrite (converted to gypsum at Nash Draw) in the western part of the Study Area. Increasing amounts of halite are present in the eastern part of the Study Area. Halite in the unnamed lower member is present over the WIPP (Figure V-4), but north and south of the WIPP at the so-called "Nash Draw Reentrants," halite is absent.

The only drill-stem test (DST) of the unnamed lower member to date was at H-16. Transmissivities of 2.9×10^{-10} m^2/s (2.7×10^{-4} ft^2/d) and 2.4×10^{-10} m^2/s (2.2×10^{-4} ft^2/d) were calculated for the first and second buildup periods of the DST (Beauheim, 1987).

The Tamarisk Member ranges in thickness from 8 to 84 m (26 to 276 ft) in southeastern New Mexico. It has a mean thickness of 40 m (130 ft) in the Study Area and is about 36 m (118 ft) thick at the WIPP. The Tamarisk consists of mostly anhydrite interbedded with thin layers of claystone and siltstone. The Tamarisk Member crops out along the southwestern part of Nash Draw. The slight structural deformation of the Tamarisk Member is similar to that of the lower units.

Unsuccessful attempts were made in two wells, H-14 and H-16, to test a 2.4 m (7.9 ft) sequence of the Tamarisk Member that consists of claystone, mudstone, and siltstone overlain and underlain by anhydrite. The permeability of the Tamarisk Member was too low to yield transmissivity values in either wells, but Beauheim (1987) estimated the transmissivity of the claystone sequence to be about two orders of magnitude less than the values for the unnamed lower member.

The uppermost member of the Rustler Formation, the Forty-niner Member, consists of anhydrite interbedded with a layer of siltstone. The unit ranges in thickness from 7 to 26 m (23 to 85 ft) and has a mean thickness of 21 m (69 ft). At the WIPP, the unit is about 20 m (66 ft) thick, has a uniform thickness throughout the Study Area, and a structure similar to that of the lower units. Tests were conducted on a claystone in the Forty-niner Member in well H-14 and on a clay unit in well H-16 (Beauheim, 1987). The tests on the claystone in well H-14 yielded a hydraulic conductivity of about 5×10^{-9} m/s (1×10^{-3} ft/d), and the tests on the clay in well H-16 yielded a hydraulic conductivity of 5×10^{-10} m/s (1×10^{-4} ft/d). Porosity for the aquitards is about 0.30.

Rustler-Salado Residuum Hydrostratigraphic Unit

A dissolution residuum is present at the contact between the Rustler and Salado Formations. In the vicinity of Nash Draw, the residuum is an unstructured, distinctive gray residue of gypsum, clay, and sandstone that grades eastward and intertongues with the clayey halite of the unnamed lower member of the Rustler Formation. Mercer (1983) concluded on the basis of brecciation at the contact that dissolution in Nash Draw occurred after deposition of the Rustler Formation. In shafts excavated at the WIPP, the residuum shows evidence of channeling and filling, fossils, and bioturbation. These features indicate that significant dissolution occurred before Rustler deposition by water fresher than the lagoonal brine from which the Salado Formation was precipitated (Holt and Powers, 1988).

The residuum ranges in thickness in the vicinity of Nash Draw from 3 m (10 ft) to about 20 m (66 ft) and averages about 8 m (26 ft) (Robinson and Lang, 1938; Mercer and Orr, 1977; Mercer, 1983). Lang (Robinson and Lang, 1938) noted that "...the structural conditions that caused the development of Nash Draw might also control the position of a body of salt water beneath it in the basal Rustler," limiting development of the residuum to the vicinity of Nash Draw. Subsequent drilling and testing has confirmed this conjecture to some extent, but evidence from wells P-14 and H-7 indicates that the residuum extends farther east than first reported (Mercer, 1983). The elongated aquifer probably thickens northward and has a range of thickness from 3 to 30 m (10 to 100 ft) and a mean thickness of about 8 m (26 ft) (Robinson and Lang, 1938). More recent information (Mercer, 1983) shows a range of 2.4 m (7.9 ft) in test hole P-14 to 33 m (108 ft) in test hole WIPP-29.

Hydraulic conductivity data for the residuum in the Study Area are concentrated in and around the WIPP with the exception of a few data points near Malaga Bend. The hydraulic conductivity ranges from 10^{-12} to 10^{-6} m/s (10^{-7} to 10^{-1} ft/d). The hydraulic conductivities at Nash Draw are higher by several orders of magnitude than the values east of the draw, ranging from 10^{-8} to 10^{-6} m/s (10^{-3} to 10^{-1} ft/d). Eastward, the range is from 10^{-12} to 10^{-9} m/s (10^{-7} to 10^{-4} ft/d). Near Malaga Bend, hydraulic conductivities were reported to be around 10^{-3} m/s (10^{2} ft/d) (Hale et al., 1954; Havens and Wilkins, 1979). A contour plot of the log hydraulic conductivities measured in the residuum indicates that two distinct zones of hydraulic conductivity occur, with the residuum becoming less permeable east of Nash Draw (Figure V-6).

Effective porosity estimates for the residuum range from 0.15 to 0.33 (Hale and Clebsch, 1958; Robinson and Lang, 1938; Geohydrology Associates, Inc.,

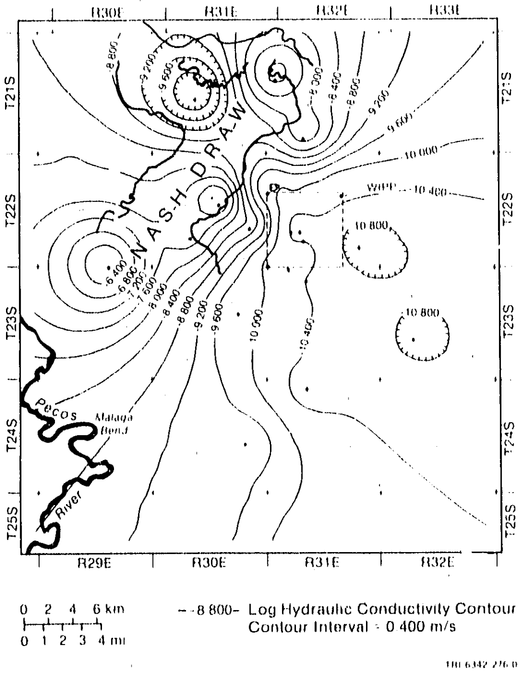


Figure V-6. Log Hydraulic Conductivities (measured in m/s) of the Rustler-Salado Residuum of the Rustler Formation in the Los Medaños Area (Brinster, in prep.).

1979; and Mercer, 1983). An average effective porosity of 0.2 has been assumed in previous work (Hale and Clebsch, 1958; and Mercer, 1983). A contour map of the potentiometric surface, in which adjusting water elevations to equivalent freshwater levels compensates for effects of variable salinity and water density, illustrates the decrease in hydraulic conductivity east of Nash Draw (Figure V-7). At the WIPP, where the hydraulic conductivity is low, the potentiometric surface is steep; west of the WIPP, where the hydraulic conductivity is several orders of magnitude higher, the surface is flatter. The hydraulic gradient in Nash Draw is 0.002. At the WIPP, the hydraulic gradient is 0.007.

The waters from the Rustler-Salado residuum are brines consisting mostly of sulfates and chlorides of calcium, magnesium, sodium, and potassium, with sodium and chloride the major constituents (Mercer, 1983). These waters have the highest concentrations of dissolved solids in the WIPP area. The lowest observed water density (1.048 g/cm^3) is at well H-7c and has a concentration of dissolved solids of 79,800 mg/ℓ. The highest observed water density (1.24 g/cm^3) has a concentration in excess of 450,000 mg/ℓ and is at test hole H-4c.

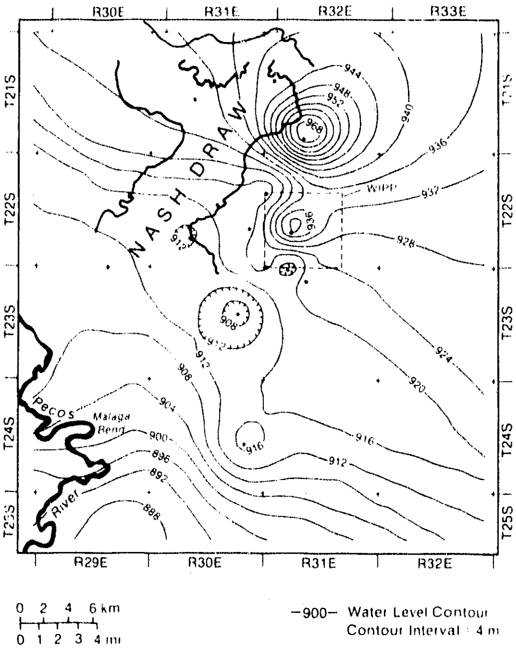


Figure V-7. Adjusted Potentiometric Surface of the Rustler-Salado Residuum in the Los Medaños Area (Brinster, in prep.).

Recharge to and discharge from the residuum to Laguna Grande de la Sal (Figure V-1) and the relationship of Surprise Spring to the lake were first investigated by Robinson and Lang (1938) and later by Hale et al. (1954) and Mercer (1983). The lake is not believed to be connected hydraulically to the residuum, because waters from wells in units under the lake have a lower chloride content than the lake water, and because wells near the lake flow from lower units (Robinson and Lang, 1938; Mercer, 1983). These observations do not necessarily mean, however, that no connection to lower aquifers exist. If the lake is a discharge area for the lower units, the low chloride content and different water chemistry would be masked by the influx of surface runoff or near-surface flow from gypsiferous members of the Rustler. The largest spring in the area, Surprise Spring, discharges into the northern end of the lake and probably gets water from the Tamarisk (Mercer, 1983).

Conclusions that the underlying units are confined in lower Nash Draw assume horizontal flow in the Culebra Dolomite Member and the residuum. Horizontal flow in confined aquifers means that flow lines are normal to vertical equipotential lines when viewed in cross section. In regions where aquifers intersect the water table (such as southern Nash Draw), recharge and discharge result in equipotential lines that parallel the recharge and discharge surfaces. Flowing wells in the region near Malaga Bend do not necessarily mean that the water-bearing unit is confined (Brinster, in prep.).

The potentiometric-surface map of the freshwater-equivalent hydraulic heads (Figure V-7) shows flow from the east, indicating recharge east of the WIPP and discharge south-southwest to the river. Overall, the gradient of the potentiometric surface of the residuum is southerly, indicating most recharge is from the north, near Bear Grass Draw (T18S, R30E) (Robinson and Lang, 1938; Lang, 1938). Recharge may occur at Clayton Basin (Figure V-1) and upper Nash Draw (Mercer, 1983). The higher potentiometric surface of the residuum shown east of the WIPP (Figure V-7) indicates flow may be from the eastern part of the Study Area toward the river, but data are insufficient to indicate if recharge is indeed occurring in this region. A possible source of recharge may be from the upper dolomitic units—the Culebra Dolomite Member and the Magenta Dolomite Member (Mercer, 1983). Some local recharge occurs in the residuum in the vicinity of Malaga Bend. An almost immediate water level rise was reported in a residuum observation well after a heavy rainstorm (Hale et al., 1954). A good hydraulic connection, possibly a sinkhole, from the surface through the Rustler Formation to the residuum was inferred in the vicinity of Malaga Bend, with local recharge occurring only under exceptional conditions (Hale et al., 1954). The residuum discharges at the southern end of Nash Draw into the Pecos River at Malaga Bend (Hale et al., 1954).

The Culebra Dolomite Hydrostratigraphic Unit

The Culebra Dolomite Member of the Rustler Formation is microcrystalline, grayish dolomite or dolomitic limestone with solution cavities (Vine, 1963). The Culebra Dolomite, where present, ranges in thickness from 4 to 11.6 m (13 to 38.3 ft) and has a mean thickness of about 7 m (23 ft). In the Study Area the Culebra has a uniform thickness of about 8 m (26 ft). The Culebra Dolomite has a shallow regional dip of less than .001 m/m to the southeast, but in the vicinity of the WIPP it dips only slightly more steeply to the northeast. Outcrops of the Culebra Dolomite occur in the southern part of Nash Draw and along the Pecos River.

Hydrologic Properties of the Culebra Dolomite Hydrostratigraphic Unit

More is known about the hydrologic properties of the Culebra Dolomite Member than any other unit in the Study Area (Mercer and Orr, 1977; Mercer and Orr, 1979; Mercer, 1983; Mercer et al., 1987; Beauheim, 1987; LaVenue et al., 1988; Davies, 1989; LaVenue et al., 1990; and Cauffman et al., 1990). A comprehensive data base has been developed (LaVenue et al., 1988, 1990).

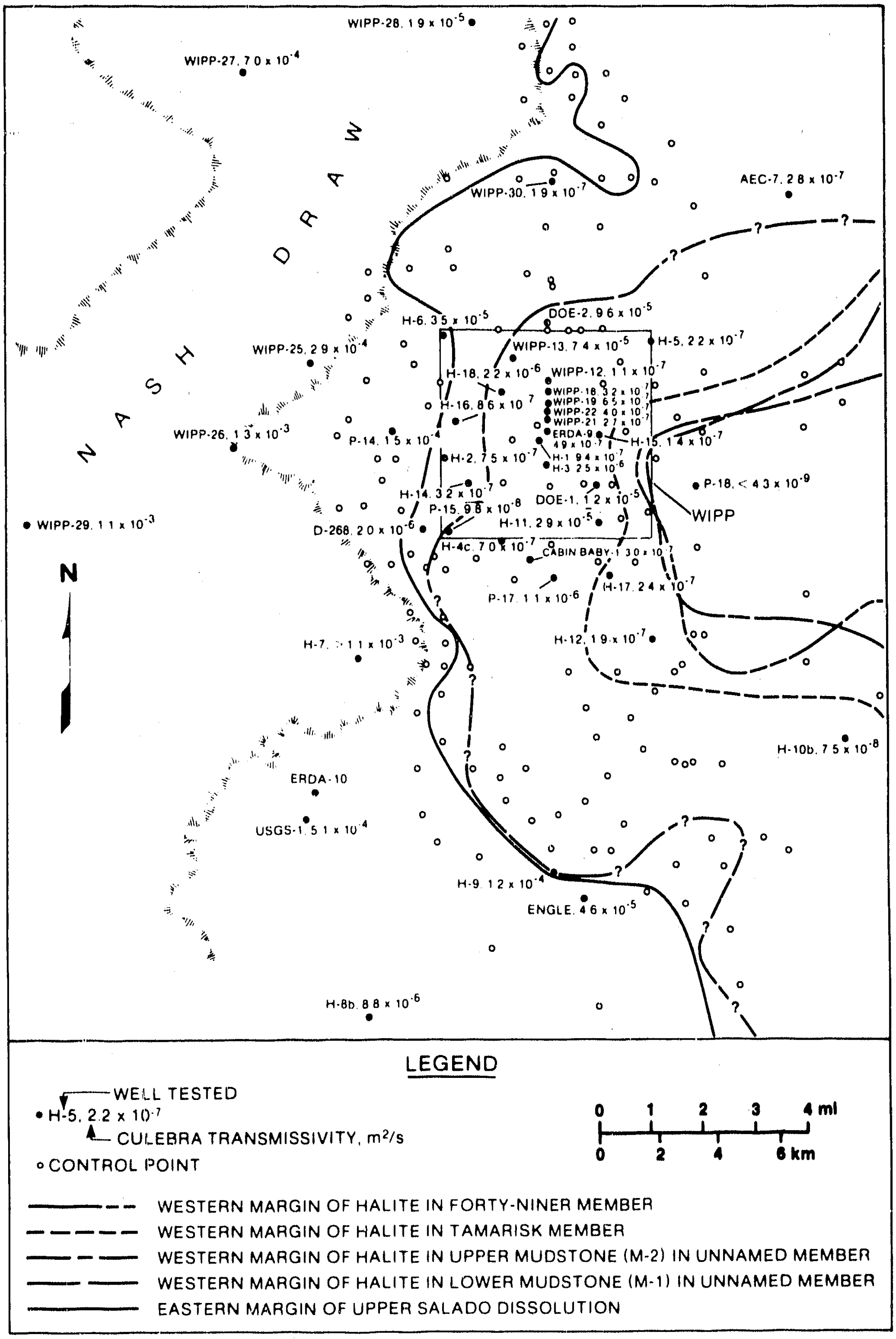
Transmissivity data exists (Figure V-8) for 20 locations around the WIPP (Mercer, 1983). Eighteen new locations have been tested since 1983, and new transmissivities have been estimated for seven previously tested locations (DOE-2, H-11, and WIPP-13) (Beauheim, 1987; Beauheim, 1986; Saulnier, 1987). Most of the data are from wells within six miles of the center of the WIPP (30 of 38), and 25 of the wells are within the proposed WIPP land withdrawal boundary.

A contour map of the log hydraulic conductivities (Figure V-9) shows the variation in the hydraulic conductivities in the Study Area. The log hydraulic conductivities were determined from the mean transmissivities at each hydropad (well cluster) (LaVenue et al., 1988) and divided by the mean Culebra Dolomite Member thickness at each hydropad. The hydraulic conductivities range from 2×10^{-10} to 2×10^{-4} m/s (6×10^{-5} to 6×10^{1} ft/d).

Variation in hydraulic conductivities is observed throughout the Study Area. This variation resulted from fracturing of the Culebra Dolomite due to subsidence associated with post-depositional dissolution of salt in the Rustler Formation (Snyder, 1985), from removal of overburden (Holt and Powers, 1988), or possibly from a combination of both processes. Several workers (Jones, 1973; Mercer, 1983; Mercer and Orr, 1977) have noted that the Rustler thickens eastward from Nash Draw as the amount of halite increases in the non-dolomitic members. Drill cores collected from east and south of the WIPP where the Rustler is thicker do not show evidence of dissolution such as that seen west of the WIPP towards Nash Draw where the Rustler is thinner (Mercer, 1983; Snyder, 1985). The thickness varies somewhat erratically in the vicinity of the WIPP (Figure V-8), although a "smooth" transition of the solution front from west to east has been reported (Beauheim, 1987).

A comparison of the Snyder model and the Holt-Powers model (Beauheim, 1987) shows that well H-18, east of the halite boundary, has a low transmissivity (consistent with the Snyder model), but WIPP-30, which has no halite, also has a low transmissivity. In addition, DOE-1 and H-11, east of H-18, have relatively high transmissivities. The low transmissivity of the Culebra Dolomite at WIPP-30 is supported by the Holt-Powers model, but this model cannot explain the high transmissivities of DOE-1 and H-11.

A value of 0.20 for the single-porosity conceptualization and for the matrix porosity of the dual-porosity conceptualization of the Culebra has been used (Haug et al., 1987) as representative of porosities ranging from 0.07 to 0.30, which were obtained from laboratory analyses of 2-cm (0.8-in) plugs taken from core samples. Two dolomite blocks taken from depths of 154 m and



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3 Figure V-8. Rustler Formation Halite and Culebra Dolomite Transmissivity around the WIPP (Lappin et al.,
4 1989).

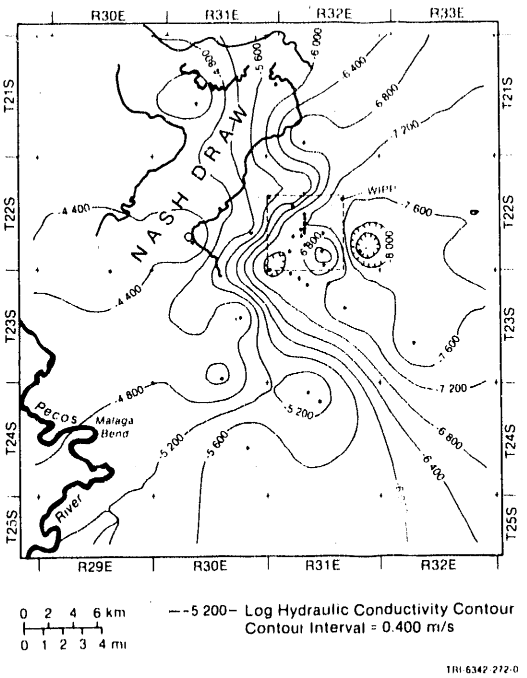


Figure V-9. Log Hydraulic Conductivities (measured in m/s) of the Culebra Dolomite Member of the Rustler Formation in the Los Medaños Area (Brinster, in prep.).

157 m (505 ft and 515 ft) during the access shaft excavation for the Gnome Project 14 km (9 mi) southwest of the WIPP revealed total porosities of 0.144 and 0.137 and effective porosities of 0.078 and 0.111 (Cooper and Glanzman, 1971).

An adjusted potentiometric-surface map of the Culebra Dolomite Member (Figure V-10) (Mercer, 1983) will be used in the preliminary modeling effort. Flow west of the WIPP is from north to south, and the flow lines are roughly parallel to the Pecos River. Northeast and east of the WIPP, data are insufficient to determine flow direction, and inference of a potentiometric surface is difficult. A few data points exist south of the WIPP, and flow is inferred to be toward the Pecos River. Flow in the Culebra Dolomite probably follows Nash Draw because of the higher transmissivity of dolomite in this area. The gradient in the upper Nash Draw area (0.003) is steeper where the Culebra Dolomite has more overburden. In the lower Nash Draw area near Malaga Bend, where the Culebra Dolomite is near the surface, the gradient is flatter (0.001 m/m). The potentiometric-surface map indicates recharge from the north, possibly at Bear Grass Draw north of Clayton Basin, where the Rustler Formation crops out, and farther south at Clayton Basin (Figure V-1), where karst activity has disrupted the Culebra Dolomite Member (Mercer,

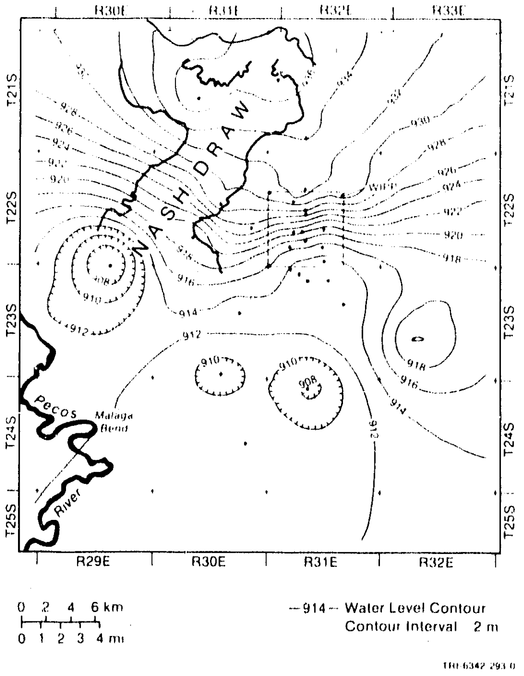


Figure V-10. Adjusted Potentiometric Surface of the Culebra Dolomite Member of the Rustler Formation in the Los Medaños Area (Brinster, in prep.).

1983). Geochemical data suggest an alternative hypothesis for the area of recharge. Uranium concentrations and uranium-234/uranium-238 activity ratios show that flow previously may have been from west to east (Lambert and Carter, 1987). Activity ratios increase from Nash Draw eastward, which would be typical of flow in that direction in a reducing environment. This trend is contrary to present day flow, suggesting that Rustler Formation groundwater is flowing from high-potentiometric-level, low-permeability areas near the WIPP, without appreciable recharge (Lambert and Carter, 1987). The Rustler Formation, therefore, is not at steady-state and recharge occurred at Nash Draw 10,000 to 30,000 years ago under conditions much wetter than today (Lambert and Carter, 1987; Lambert and Harvey, 1987; Lambert, 1987).

Recharge from precipitation infiltrating through the overburden seems unlikely under present conditions. Comparisons of recharge data from two modern basins similar to the Delaware Basin lead to the conclusion that definitive values for recharge to the confined Rustler Formation probably cannot be determined from available data (Lambert and Harvey, 1987).

Discharge from the Culebra Dolomite Member in the Study Area is to the west-southwest, either into the Pecos River at Malaga Bend, into the Balmorhea-

Loving Trough, or into both (Figure V-1). Salinity of the Pecos River increases at Malaga Bend, which has been described as a discharge area for the region (Hale et al., 1954; Hale and Clebsch, 1958; Havens and Wilkins, 1979; Mercer, 1983). The increase in salinity could be from the residuum's local discharge instead of regional conditions. Culebra Dolomite water might be discharging toward the Balmorhea-Loving Trough. At this time, rates of discharge from the region can only be estimated because no seepage runs have been made on the Pecos River.

The quality of water from the Culebra Dolomite Member is marginal; this water is used locally by ranches for livestock watering. Total dissolved solids range from 3,200 to 420,000 mg/ℓ at test holes H-8b and P-18, respectively. A series of analyses of groundwater flow in the vicinity of the WIPP examined the effects of density-related, flow-driving forces and the effects of boundary conditions (Davies, 1989). Two-dimensional model simulation showed that density-related effects were unimportant at the WIPP and west of the WIPP but were important north, northeast, and south of the WIPP. Simulations of boundary effects showed that if the Culebra Dolomite Member has a relatively low permeablity east and northeast of the WIPP, the western part, including the WIPP, is not affected by conditions on the boundary. These analyses also showed that if the Culebra Dolomite is assumed to be confined throughout the region, a change in the Pecos River elevation will eventually affect the potentiometric surface in the Culebra Dolomite at the WIPP (Davies, 1989).

Hydrogeology of the Magenta Dolomite Hydrostratigraphic Unit

The Magenta Dolomite Member of the Rustler Formation is a fine grained, greenish-gray dolomite with reddish-purple layers. This member ranges in thickness from 4 to 8 m (13 to 26 ft) and has a mean thickness of 6 m (19 ft). The Magenta is about 6 m (19 ft) thick at the WIPP. The unit thickens slightly in the central part of the Study Area and thins to the southeast. The Magenta crops out along most of Nash Draw and has a structure similar to the underlying units. Groundwater yield is low, and available data reflect a limited interest in the member. Fourteen wells have been tested and reported (Mercer, 1983; Beauheim, 1987).

Hydrologic Properties of the Magenta Dolomite Hydrostratigraphic Unit

The Magenta Dolomite Member is unsaturated at outcrops along Nash Draw. Spring deposits along the eastern rim of the Draw are thought to have formed when precipitation drained from the surface into fractures of the Rustler Formation, dissolved soluble layers, and emerged at the edge of the Draw, where the water evaporated (Bachman, 1981). At Nash Draw, the Magenta Dolomite is almost in contact with the Culebra Dolomite, separated only by a few meters of dissolution residue.

Only 14 values of transmissivity have been measured from the Magenta Dolomite Member, ranging over five orders of magnitude from 4.0×10^{-9} to 4×10^{-4} m^2/s (4×10^{-3} to 4×10^{2} ft^2/d). The hydraulic conductivity for the Magenta ranges from 5.0×10^{-10} to 5.0×10^{-5} m/s (1×10^{-4} to 1×10^{1} ft/d). The largest transmissivity tested (4.0×10^{-4} m^2/s) (6×10^{-3} ft^2/d) was at WIPP-25 (at the edge of Nash Draw west of the WIPP). The lowest transmissivity tested (6.0×10^{-9} m^2/s [6×10^{3} ft^2/d]) was at test hole H-8. Test holes H-7a and WIPP-28 were drilled in an unsaturated part of the Magenta Dolomite Member. Examination of a core of WIPP-28 revealed bedding plane partings and fractures filled with gypsum (Mercer, 1983).

A contour map of log hydraulic conductivities of the Magenta Dolomite Member (Figure V-11) shows a decrease in conductivity from west to east, with slight indentations of the contours north and south of the WIPP that correspond to the topographic inlets observable at the surface. A preliminary statistical analysis of the correlation of overburden thickness to hydraulic conductivity shows a poor correlation ($r = -0.5$). The poor correlation may result from the way the material surrounding the Magenta Dolomite Member has been dissolved and from the subsequent deposition of gypsum in parting planes and fractures.

No porosity measurements have been made on the Magenta Dolomite Member, but a porosity of 0.20 was assumed by Beauheim (1987). This value is slightly high for intact dolomite but may be close to an average porosity for dolomite that has undergone some secondary porosity development.

Contours of the potentiometric-surface map (Figure V-12) representing freshwater-equivalent heads indicate a southwestward flow in the northeastern part of Nash Draw and a gradient of 0.003. Flow is almost westward across the WIPP, with a gradient of 0.004. The Magenta Dolomite is absent in the southwestern part of the Draw and, because no springs issue along the rim of the Draw, the groundwater is assumed to flow into lower units through fractures.

The potentiometric map indicates recharge to the Magenta Dolomite Member probably occurs to the north, possibly in Clayton Basin (Figure V-1) or farther north at Bear Grass Draw where the Rustler crops out (Mercer, 1983). Apparent recharge to the east of the WIPP may be an artifact of variable water-quality corrections and density effects on the static-head estimate (Mercer, 1983). Discharge is probably into the lower units (Tamarisk Member and Culebra Dolomite Member).

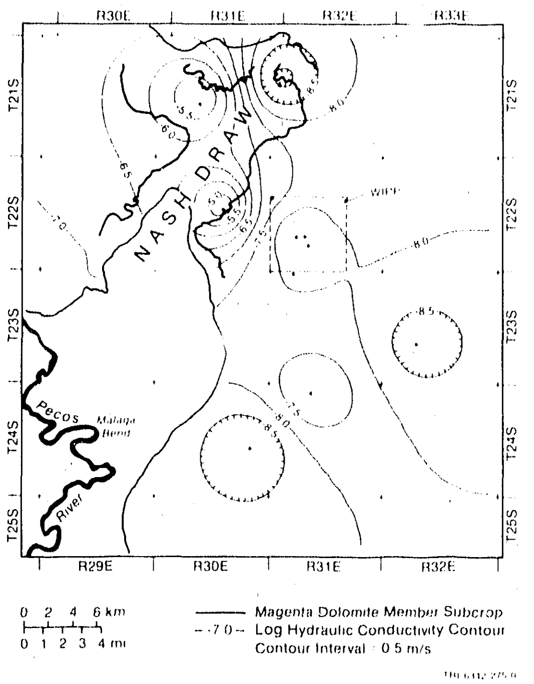


Figure V-11. Log Hydraulic Conductivities (measured in m/s) of the Magenta Dolomite Member of the Rustler Formation in the Los Medaños Area (Brinster, in prep.).

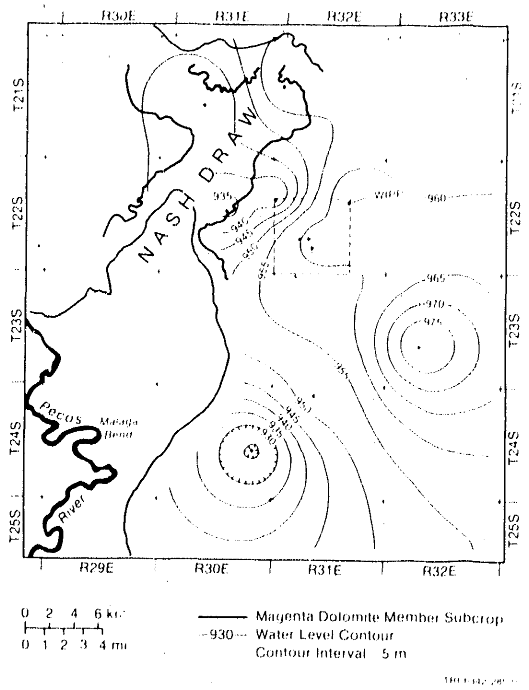


Figure V-12. Adjusted Potentiometric Surface of the Magenta Dolomite Member of the Rustler Formation in the Los Medaños Area (Brinster, in prep.).

Water density varies from 1.004 g/cm^3 (only slightly saline) at test hole H-9a in the southern part of the Study Area to 1.171 g/cm^3 at test hole H-10 southeast of the WIPP. The Magenta Dolomite water-quality distribution is not as well defined as the Culebra Dolomite water-quality distribution but is, nevertheless, distinguishable and reflects the degree of dissolution of underlying halite (Mercer, 1983).

Hydrogeology of the Supra-Rustler Rocks

Several rock units younger than the Ochoan Rustler are present in the Study Area. These units are of little hydrologic importance because they are not aquifers and, indeed, are dry throughout most of the Study Area (Lappin et al., 1989). However, the units should be considered because saturation could occur in the upper units as a result of climatic changes or from a breach of a pressurized brine reservoir. The Dewey Lake Red Beds of the Permian Period and the overlying Mesozoic, Cenozoic, and Holocene material are lumped as one hydrologic unit for regional modeling purposes, and more detailed discussion of these units can be found in references cited.

Conformably overlying the Rustler Formation are the uppermost Ochoan rocks, the Dewey Lake Red Beds (Pierce Canyon Red Beds in Vine, 1963), consisting of reddish-brown, alternating fine-grained sandstones and siltstones cemented with calcite and gypsum. Bedding can be structureless or cross-laminated, and ripple marks and mud cracks can be present. In the Study Area, the Dewey Lake Red Beds are absent in Nash Draw, are as much as 60 m (196 ft) thick where present west of the WIPP, and can be over 200 m (656 ft) thick east of the WIPP. The Dewey Lake Red Beds are unconformably overlain by Mesozoic rocks that consist of the Triassic Dockum Group and Cretaceous sediments. These rocks and sediments are mostly absent west of Nash Draw; the thickness ranges to over 100 m (328 ft) in western Lea County. Overlying the Mesozoic rocks are Cenozoic materials consisting of the Pliocene Ogallala Formation on the extreme eastern part of the Study Area. Overlying these units unconformably are the Quaternary Gatuña Formation and the informally named Mescalero caliche. Overlying these units are Holocene soils. Where present, the supra-Rustler units collectively range in thickness from 4 to 536 m (13 to 1758 ft). An isopach map of the region shows the rock units thicken to the east, forming a uniform wedge of overburden across the Study Area (Brinster, in prep.).

Drilling in the Dewey Lake Red Beds has not identified any continuous saturated zone. Some localized zones of relatively high permeability were identified by loss of drilling fluids at DOE-2 and H-3d (Mercer, 1983; Beauheim, 1987). Some thin, lenticular, saturated, perched and semiperched sands were identified in the upper Dewey Lake Red Beds at wells H-1, H-2, and H-3 (Mercer and Orr, 1979; Mercer, 1983). The only wells producing water from the Dewey Lake Red Beds in quantities sufficient to water livestock are the James Ranch wells, Fairview well, and Pocket well.

Preliminary hydrologic properties of supra-Rustler rocks are difficult to determine because of the lack of long-term pump tests and lab tests. The hydraulic conductivity of these rocks, assuming saturation, is estimated to be 10^{-11} m/s (10^{-6} ft/d), similar to the hydraulic conductivity of the Forty-niner Member. The porosity is about 0.20, which is representative of fine-grained sandstone. Storativity (storage coefficient) is assumed to be 10^{-4}. Water density is assumed to be similar to that of the water in the Magenta Dolomite Member.

The supra-Rustler units are recharged locally by water percolating downward through fractures to bedding planes and fine-grained lenticular sandstones; the units discharge to lower zones (Mercer, 1983). Lateral movement of groundwater is limited by the lenticular and discontinuous nature of the sands.

Surface Water

The Pecos River drainage system, the principal surface-water feature in southeastern New Mexico, flows southeastward in Eddy County approximately parallel to the axis of the Delaware Basin, draining into the Rio Grande in western Texas. In the vicinity of the WIPP, the drainage system includes small ephemeral creeks and draws and has a drainage area of about 50,000 km^2 (20,000 mi^2). The Pecos River, which is about 20 km (12 mi) southwest of the WIPP, flows diagonally across the southwestern corner of the Los Medaños Study Area and has the lowest surface elevation of the Study Area.

Several shallow lakes in Nash Draw cover an area of about 16 km^2 (6 mi^2) north of Malaga Bend and southwest of the WIPP. The largest lake, Laguna Grande de la Sal, has existed for many years. Since 1942, smaller, intermittent, saline lakes have formed in closed depressions north of Laguna Grande de la Sal as a result of effluent from potash mining and oil-well development in the area (Hunter, 1985). Effluent also has enlarged Laguna Grande de la Sal. The lakes collect precipitation, surface drainage, and groundwater discharge from springs and seeps. The rate of discharge from the groundwater to the lakes in the area is estimated to be 0.67 m^3/s (24 ft^3/s) (Hunter, 1985). Very little, if any, of the surface water from Nash Draw reaches the Pecos River (Robinson and Lang, 1938; Lambert, 1983).

The only spring of importance in the Study Area is Surprise Spring at the northern edge of Laguna de la Sal. In 1942, the spring discharged at a rate of less than 0.01 m^3/s (1 ft^3/day), and this rate has since declined (Lambert and Harvey, 1987; Hunter, 1985).

Summary

The important hydrostratigraphic units for regional groundwater flow in the vicinity of the WIPP are, in ascending order, the Rustler-Salado residuum and the Culebra and Magenta Dolomite Members of the Rustler Formation.

The Rustler-Salado residuum is the first hydrostratigraphic unit above the Salado Formation and consists of residue from dissolution of upper Salado and lower Rustler Formation halite. The hydraulic conductivity ranges within an order of magnitude from 10^{-12} m/s (10^{-7} ft/d) in the vicinity of the WIPP to 10^{-6} m/s (10^{-1} ft/d) in Nash Draw. The mean effective porosity of the unit is about 0.20. The unit is under confined conditions over most of the area but under water table conditions in the vicinity of Malaga Bend in the southwestern corner of the Study Area. The residuum recharges north of the WIPP and discharges to the southwest.

The Culebra Dolomite Member of the Rustler Formation is a microcrystalline dolomite with relatively consistent thickness, around 8 m (26 ft), and is present throughout the Study Area. The Culebra is under confined conditions in the vicinity of the WIPP and under water table conditions near Malaga Bend at the lower end of Nash Draw. The log hydraulic conductivity ranges within an order of magnitude from -10 in the eastern part of the Study Area to -4 in the western part of the Study Area in Nash Draw and near Malaga Bend. The average porosity of the unit is about 0.20. The Culebra recharges from the north and east and discharges to the southwest.

The Magenta Dolomite Member of the Rustler Formation is similar in composition and thickness to the Culebra Dolomite Member but is not present in the western part of the Study Area in Nash Draw. Log hydraulic conductivity ranges within an order of magnitude from about -9 to -4. Effective porosity of the Magenta is about 0.20. The Magenta recharges from the north and possibly east and discharges through fractures into the Tamarisk and Culebra Dolomite Members.

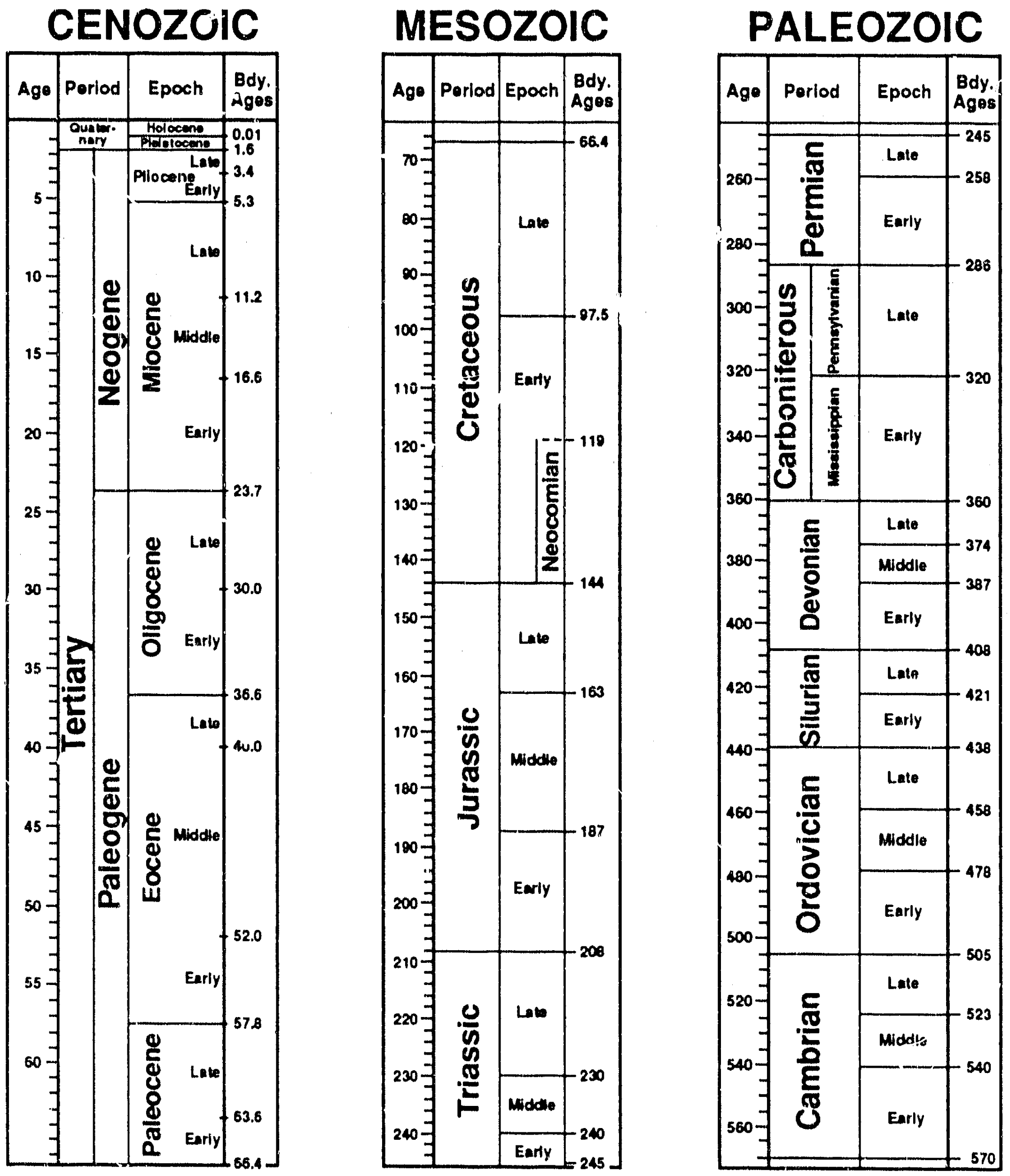
The units above the Rustler are considered as one hydrostratigraphic unit with a composite hydraulic conductivity based on values for all overlying units. The unit is unsaturated except for some locally perched sands that provide water for a few livestock wells. Recharge to the supra-Rustler units is probably from precipitation. A 3-m (10-ft) thick unit of caliche that is present throughout the area allows very little recharge to the Rustler Formation.

LONG-TERM CLIMATE VARIABILITY

Changes in the climate of southeastern New Mexico during the next 10,000 years may affect repository performance. In particular, changes in the average level of precipitation could affect recharge to the Rustler Formation and the currently unsaturated overlying units. The following discussion, taken from Marietta et al. (in prep.), presents the WIPP performance-assessment approach to evaluating long-term climatic variability.

Available long-term climate models are incapable of resolution on the spatial scales required (e.g., Hansen et al., 1988; Mitchell, 1989), and limits on future precipitation are based instead on known and modeled past extremes. Much of the available paleoclimatic data only record gradual shifts in long-term average levels of precipitation, and these limits do not reflect the high variability apparent in the modern short-term data (e.g., Hunter, 1985).

A fundamental assumption, analogous to that made by Spaulding (1985) in a study of climatic variability at the Nevada Test Site, is that climatic extremes of the next 10,000 years will not exceed those associated with glaciations and deglaciations that have recurred repeatedly in the northern hemisphere since the late Pliocene (Figure V-13), approximately 2.5 million years ago. The possibility that human-induced changes in the composition of the earth's atmosphere may influence future climates complicates projections of this cyclic pattern into the future, but, as presently modeled, fluctuations during the next 10,000 years will remain within past limits. Currently available models of the greenhouse effect do not predict long-term global climatic changes greater than those during the last 2.5 million years (e.g., Mitchell, 1989). The highest past precipitation levels in the American Southwest, up to twice those of the present, occurred during full-glacial conditions associated with global cooling (e.g., Van Devender et al., 1987; other sources cited below). Greenhouse models, however, predict average equilibrium global warming of 1.8 to 5.2°C for carbon dioxide concentrations twice present levels (Mitchell, 1989), a condition that could delay the start of renewed glaciation. Model predictions in the literature of precipitation trends accompanying greenhouse warming are less consistent and less reliable than temperature predictions, but none suggest significantly higher levels of precipitation in southern New Mexico than those of the present (Washington and Meehl, 1984; Wilson and Mitchell, 1987;



All Ages in Millions of Years

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3 Figure V-13. Geologic Time Scale (simplified from Geological Society of America, 1984).

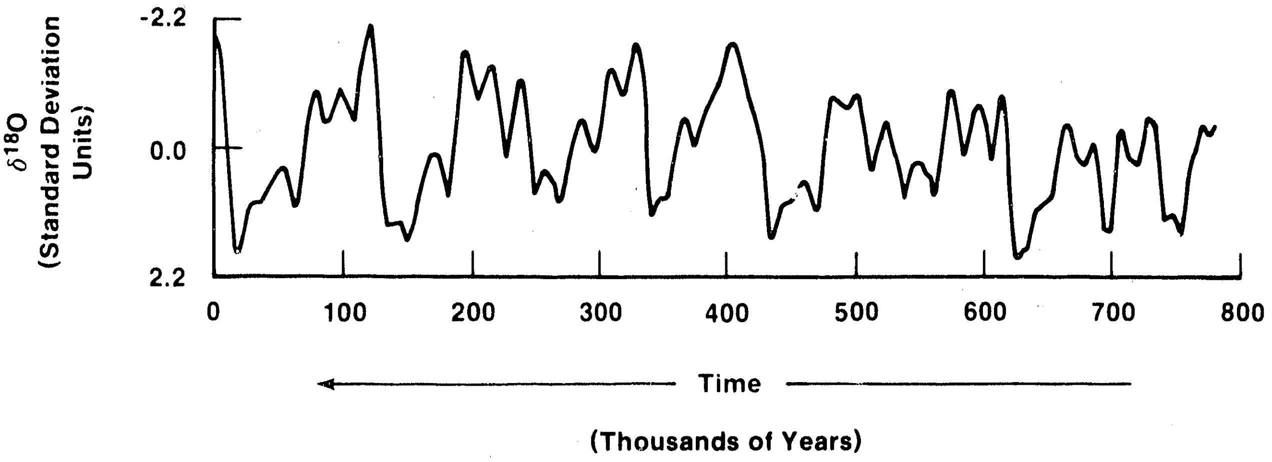
Schlesinger and Mitchell, 1987). Because long-term increases in recharge are improbable without increases in precipitation, the highest-risk climatic change that will be considered here is, therefore, a return to the glacial extremes of the past.

Data that can be used to interpret paleoclimates in the American Southwest come from a variety of sources and indicate alternating arid and sub-arid to sub-humid climates throughout the Pleistocene. Prior to 18,000 years ago, radiometric dates are relatively scarce, and the record is incomplete. From 18,000 years ago to the present, however, the climatic record is relatively well-constrained by floral, faunal, and lacustrine data. These data span the transition from the last full-glacial maximum to the present interglacial period, and, given the global consistency of glacial fluctuations as described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

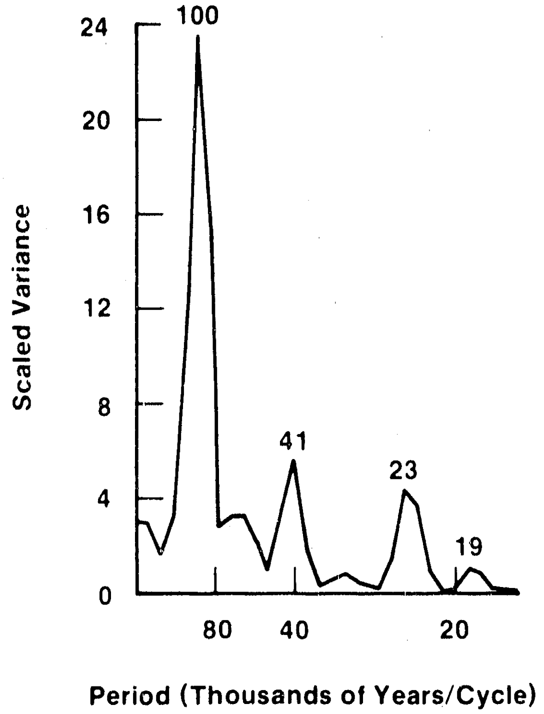
Variability in Global Climate Over the Last 2.5 Million Years

Core samples of datable marine sediments provide a continuous record that reveals as many as 50 glaciation/deglaciation events in the last 2.5 million years. Specifically, correlations have been made between major glacial events and variables such as oceanic ratios of oxygen-18/oxygen-16 as measured in the remains of calcareous foraminifera and the record of past sea-surface temperatures as determined from planktonic assemblages (Ruddiman and Wright, 1987).

Oxygen isotope ratios provide the most direct evidence, because they reflect past volumes of glacial ice (Imbrie et al., 1984). Evaporation fractionates oxygen-18 and oxygen-16 isotopes in sea water, producing a vapor relatively enriched in oxygen-16 and residual seawater relatively enriched in oxygen-18. Glacial ice sheets store large volumes of oxygen-16-enriched meteoric water, preventing the remixing of the two isotope fractions and significantly altering oxygen isotope ratios in the world's oceans. Foraminifera preserve samples of past isotope ratios when they extract oxygen from sea water and incorporate it into calcareous body parts. Abundant fossil remains permit the construction of detailed records such as that shown in Figure V-14a, covering the last 780,000 years. High levels of oxygen-18 reflect glacial maxima, and low levels reflect warm interglacial periods. Because the largest volumes of glacial ice were incorporated in the North American sheet, isotopic fluctuations can be interpreted directly as a first order record of North American glaciation and deglaciation (Mix, 1987; Ruddiman and Wright, 1987). Because the correlation is quantitative, the isotopic record



a. $\delta^{18}O$ variations from five deep-sea core samples. Data have been normalized, stacked, and smoothed with a 9-point Gaussian filter (Imbrie et al., 1984).



$$\delta^{18}O = 1000 \times \frac{\left({}^{18}O/{}^{16}O_{sample} - {}^{18}O/{}^{16}O_{reference}\right)}{{}^{18}O/{}^{16}O_{reference}}$$

b. Spectral analysis of $\delta^{18}O$ record in Figure a, showing periodicity of glaciation and deglaciation (after Imbrie, 1985).

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Figure V-14. Foraminiferal Oxygen Isotope Record of the Last 780,000 Years.

indicates that most glacial events, including the most recent one, have been of roughly equivalent intensity. The correlation also indicates that the present value is at or near that of a glacial minimum.

Sea-surface temperature records, although not as closely tied to glacial events, show the same alternating pattern. Temperatures at the surface of northern hemisphere oceans, as determined from the fossil assemblages of planktonic foraminiferal species, were measurably colder during glaciation and warmer during interglacial periods (Ruddiman, 1987).

The causes of glaciation and deglaciation are complex and not fully understood (Ruddiman and Wright, 1987), but the oxygen isotope record indicates a strong periodicity of climatic variation. Spectral analysis of the isotopic variation for the last 780,000 years shows that within that time the primary control on the periodicity of glacial events has been variation in global insolation (the amount of energy received from the sun) caused by irregularities in the earth's orbit. Glacial intervals of 19,000, 23,000, 41,000, and 100,000 years (Figure V-14b) correspond to calculated periodicities between summer insolation minima in the northern hemisphere of 19,000 and 23,000 years related to the precession of the earth's axis, 41,000 years related to the tilt of earth's axis, and 94,000, 125,000 and 413,000 years related to the eccentricity of the earth's orbit (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984; Imbrie, 1985). Calculations based on astronomical observations indicate that orbital parameters have not changed significantly in the last 5 million years (Berger, 1984), and geological evidence suggests they may have been stable for as long as 300 million years (Anderson, 1984; Heckel, 1986).

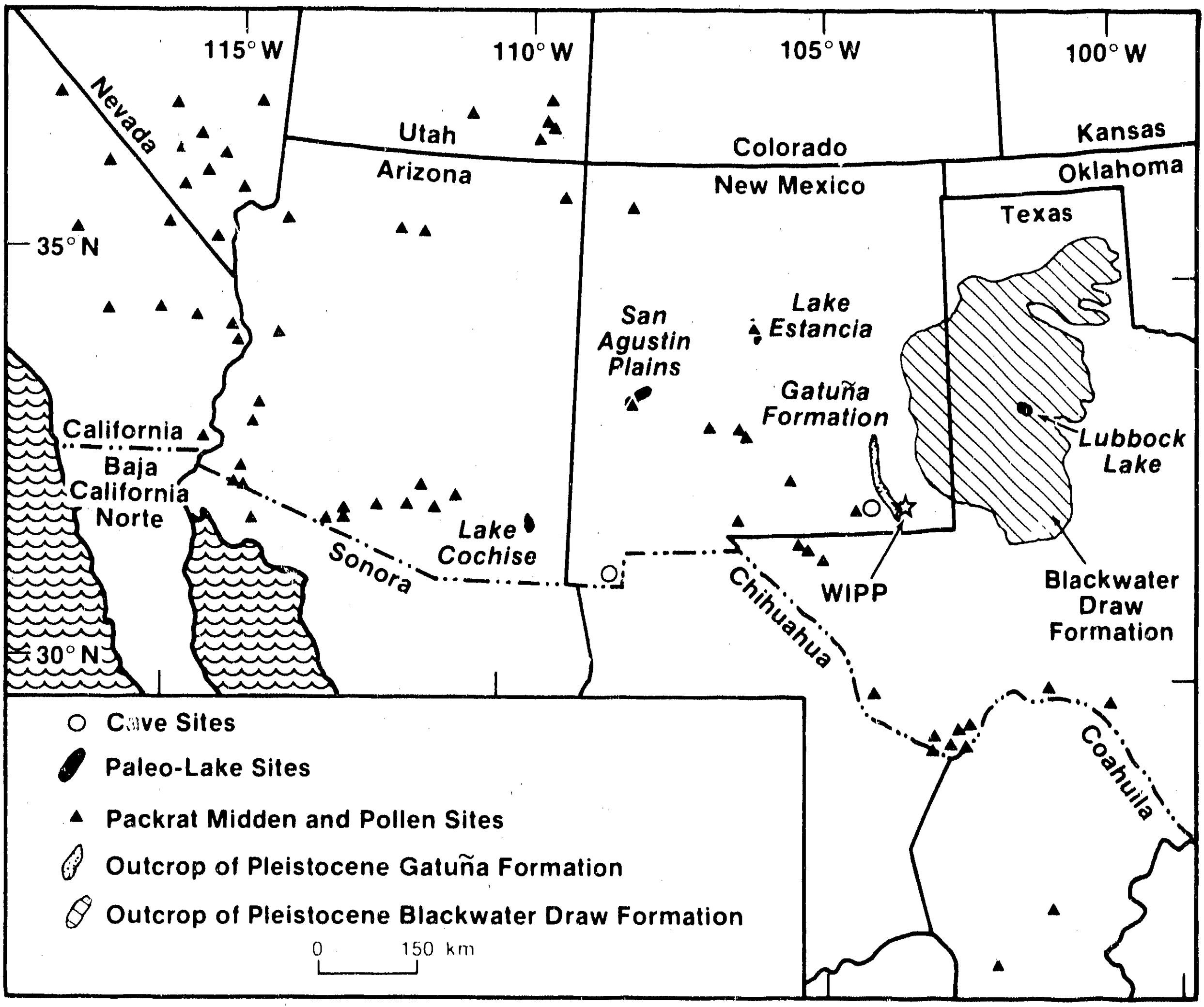
Longer-term global climatic changes, such as the beginning of the present pattern of glaciation and deglaciation 2.5 million years ago, have been attributed to changes in the configuration of the earth's continents, which in turn controls both global circulation patterns and the potential distribution of ice sheets (e.g., Crowell and Frakes, 1970; Caputo and Crowell, 1985). Continental masses move at plate-tectonic rates of centimeters per year, several orders of magnitude too low to affect glacial processes within the next 10,000 years. Vertical uplift or subsidence of large continental regions may also affect global climate by changing circulation patterns (e.g., Boulton, 1989; Ruddiman and Kutzbach, 1989), but, again, maximum uplift rates are at least an order of magnitude too slow to change present circulation patterns within the next 10,000 years.

The long-term stability of the cycles of glaciation and deglaciation provides the basis for concluding that climatic extremes of the next 10,000 years will remain within past limits. The relative amplitudinal consistency (Figure V-14a) implies that future glaciations will be comparable in severity to past ones. The periodicity of the pattern indicates that, although glacial minima such as that of the present are relatively brief, glacial advances are slow, and the next maximum will not occur for many tens of thousands of years. Predictions about the precise timing of future glacial events are complicated by uncertainties about feedback processes in the growth of ice sheets. Extrapolation of the isotopic curve, however, using a relatively simple model for non-linear climate response to insolation change, suggests that, in the absence of anthropogenic effects, the next glacial maximum will occur in approximately 60,000 years (Imbrie and Imbrie, 1980). These observations, combined with the climatic data discussed below, justify the choice of the late-Pleistocene full-glacial climate as a conservative upper limit for precipitation during the next 10,000 years.

Pleistocene and Holocene Climates of the Southwestern United States

Early and middle Pleistocene paleoclimatic data for the southwestern United States are incomplete and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum, 22,000 to 18,000 years ago. Stratigraphic and soil data from several locations, however, indicate that cyclical alternation of wetter and drier climates in the Southwest had begun by the early Pleistocene. Fluvial gravels in the Gatuña Formation (Figure V-15) exposed in the Pecos River Valley of eastern New Mexico indicate wetter conditions 1.4 million years ago and again 600,000 years ago (Bachman, 1987). The Mescalero caliche, exposed locally over much of southeastern New Mexico, suggests drier conditions 510,000 years ago, and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions again later in the Pleistocene (Bachman, 1981, 1987). The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas (Figure V-15), time-correlative to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 million years ago and continuing to the present (Holliday, 1989a). The duration, frequency, and total number of Pleistocene climatic cycles in the Southwest have not been established.

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from six independent lines of evidence dated using carbon-14 techniques: plant communities preserved in packrat middens throughout the Southwest, including sites in Eddy and Otero Counties, New Mexico (Van Devender, 1980; Van Devender et al., 1984, 1987); pollen assemblages from lacustrine deposits in western New Mexico and other



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3 Figure V-15. Location Map for Paleoclimate Data. Data references cited in text.

locations in the Southwest (Markgraf et al., 1984; Van Devender et al., 1987); gastropod assemblages from western Texas (Pierce, 1987); ostracode assemblages from western New Mexico (Markgraf et al., 1984); paleo-lake levels throughout the Southwest (Markgraf et al., 1983, 1984; Benson and Thompson, 1987; Holliday and Allen, 1987; Bachhuber, 1989; Waters, 1989; Enzel et al., 1989); and faunal remains from caves in southern New Mexico (Harris, 1987, 1988). Figure V-15 shows the locations of key sites discussed here and in the references cited. Figure V-16 summarizes the climatic interpretation developed from the data.

Because decreases in temperature and increases in precipitation produce similar environmental changes, not all data cited uniquely require the paleoclimatic interpretation presented here. For example, lake-level increases can, in theory, result solely from decreased evaporation at lower temperatures. Interpretations drawn individually from each of the data sets are consistent with the overall trends, however, and the pattern of change is confirmed by global climate models (Spaulding and Graumlich, 1986; Kutzbach and Guetter, 1986; COHMAP Members, 1988). Furthermore, specific floral and faunal assemblages are sufficiently sensitive to precipitation and temperature effects to distinguish between the two (e.g., Van Devender et al., 1987; Pierce, 1987). The paleoclimates described here are those that best explain data from all sources.

Prior to the last glacial maximum 22,000 to 18,000 years ago, evidence from mid-Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of species such as the desert tortoise that are now restricted to warmer climates, suggests hot summers and mild, dry winters (Harris, 1987, 1988). Lacustrine evidence confirms the interpretation of a relatively dry climate prior to and during the glacial advance. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24,000 years ago (Bachhuber, 1989), and water depths in lakes at higher elevations in the San Agustin Plains in western New Mexico did not reach a maximum until between 22,000 and 19,000 years ago (Forester, 1987).

Ample floral and lacustrine evidence documents cooler and wetter conditions in the Southwest during the glacial peak (e.g., Benson and Thompson, 1987; Van Devender et al., 1987; Pierce, 1987; Bachhuber, 1989). These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene continental glaciations advanced farther southwest than northeastern Kansas, and the most recent, late-Wisconsin ice sheet reached its limit in South Dakota, roughly 1200 km (approximately 745 miles) from the WIPP (Andrews, 1987). Discontinuous alpine glaciers formed at the highest

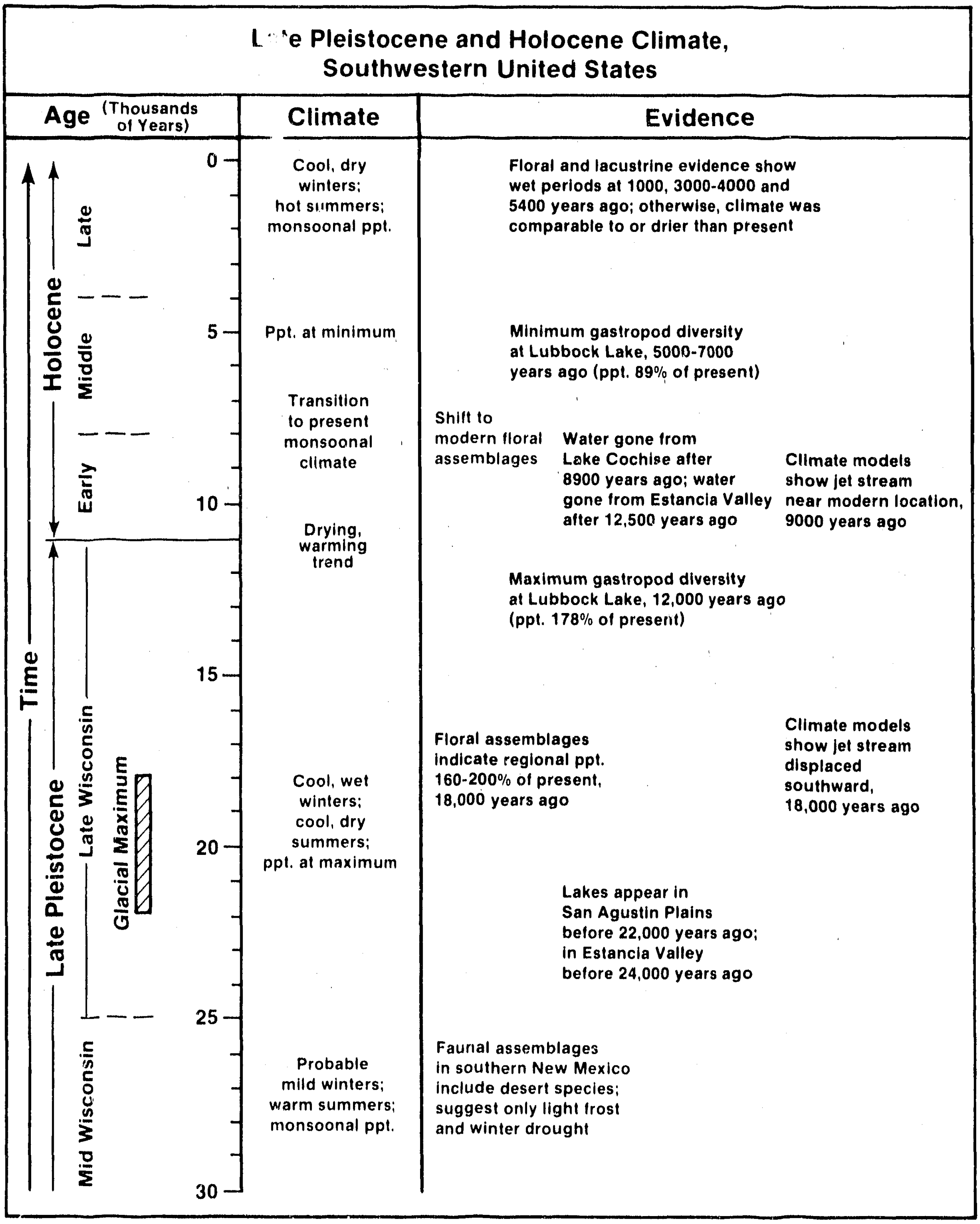

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Figure V-16. Late Pleistocene and Holocene Climate, Southwestern United States (from Marietta et al., in prep.). Time scale after Van Devender et al., 1987. Climate references cited in text.

elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions, and had little influence on regional climate at lower elevations. The closest such glacier to the WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, 220 km (approximately 135 miles) to the northwest (Richmond, 1962).

Global climate models indicate that the dominant glacial effect in the Southwest was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north (Figure V-17) (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986; COHMAP members, 1988). At the glacial peak, major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

Field evidence does not support the suggestion (Galloway, 1970, 1983; Brakenridge, 1978) that higher lake levels and changed faunal and floral assemblages at the glacial maximum could have resulted solely from lowered temperatures. Plant communities indicate the decrease in mean annual temperatures below present values was significantly less than the 7 to 12°C required by cold and dry climate models (Van Devender et al., 1987). Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5°C below present values (Pierce, 1987). Both floral and faunal evidence indicate annual precipitation throughout the region was 1.6 to 2.0 times more than today (Spaulding and Graumlich, 1986; Pierce, 1987; Van Devender et al., 1987). Floral evidence also suggests winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon. Piñons, oaks, and junipers grew at lower elevations throughout southern New Mexico (Van Devender et al., 1987), probably including the vicinity of the WIPP.

The jet stream shifted northward following the gradual retreat of the ice sheet after 18,000 years ago (Figure V-17), and the climate responded accordingly. By the Pleistocene/Holocene boundary approximately 11,000 years ago, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today (Van Devender et al., 1987). Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the ice sheet had retreated into northeastern Canada in the early Holocene.

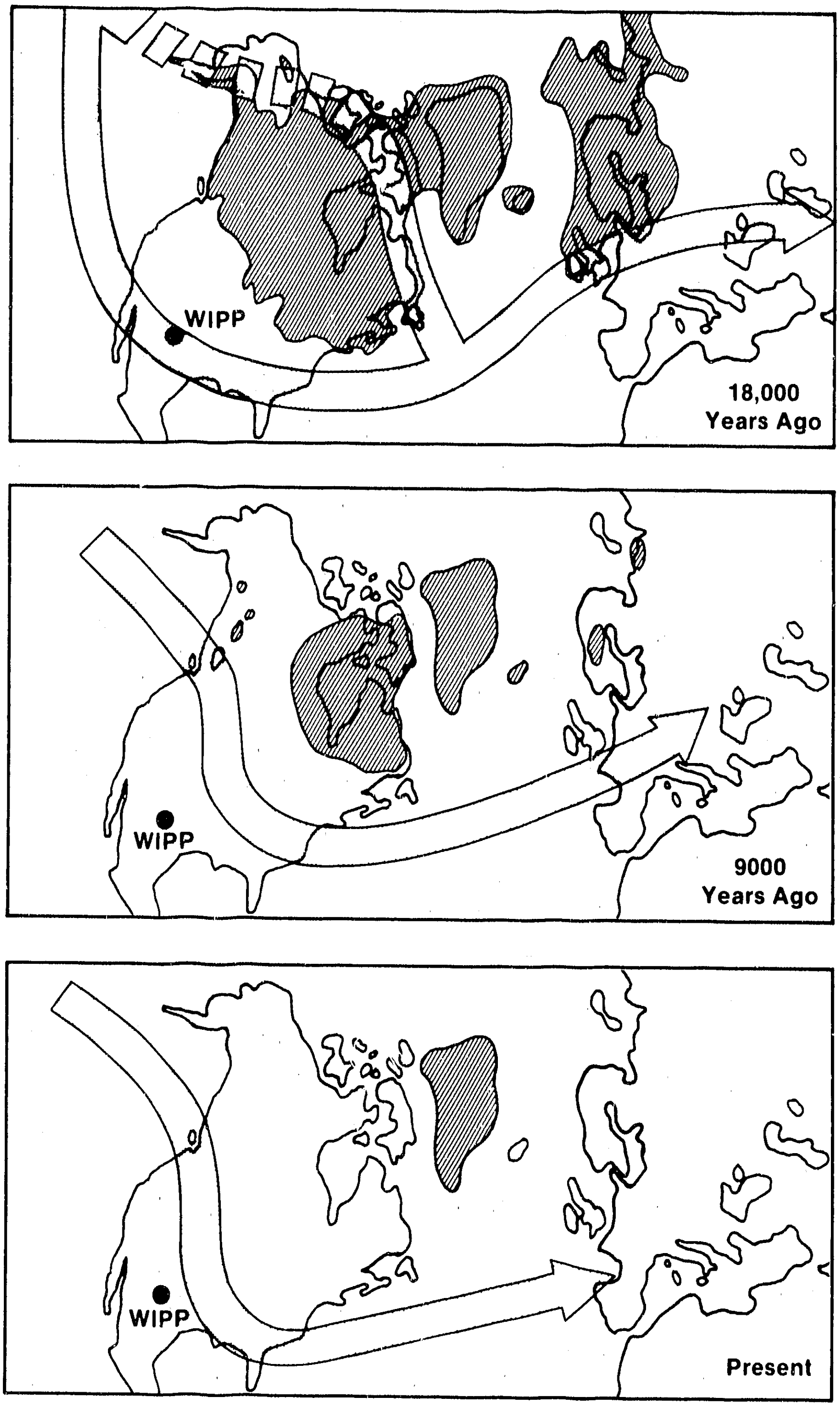

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Figure V-17. Distribution of Northern Hemisphere Ice Sheets and Modeled Average Position of Jet Stream 18,000 Years Ago, 9000 Years Ago, and Present (from COHMAP Members, 1988). Ice shown with dark pattern, jet stream shown with arrow (broken where disrupted or weak).

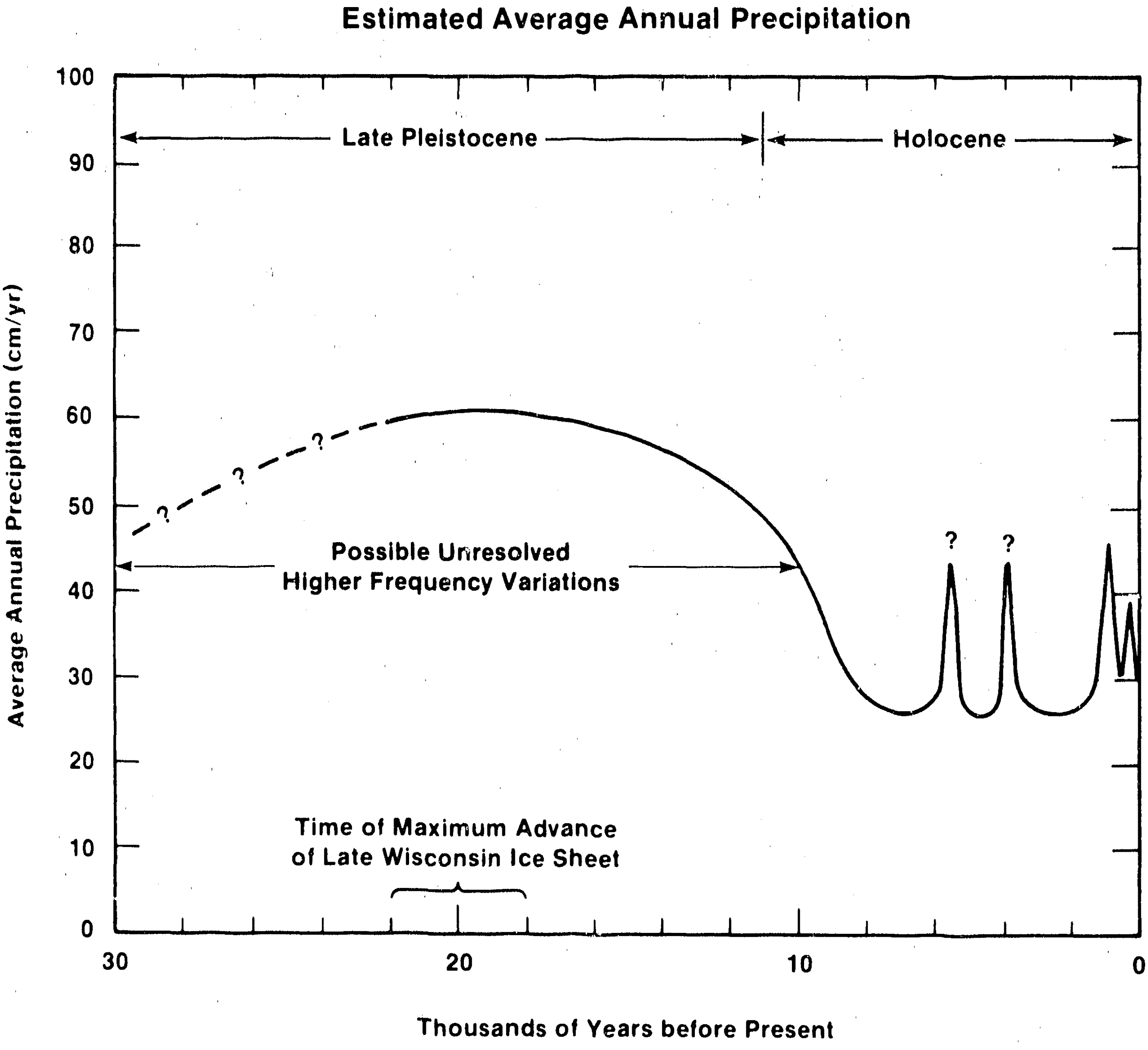
Evidence for an early Holocene drying trend comes from several sources. Permanent water disappeared from late-Pleistocene lakes in the Estancia Valley after 12,500 years ago (Bachhuber, 1989), and from Lake Cochise (the modern Willcox Playa) in southeastern Arizona after 8900 years ago (Waters, 1989). Water remained in lakes in the higher elevation San Agustin Plains until 5000 years ago, but ostracode assemblages suggest an increase in salinity by 8000 years ago, and the pollen record shows a gradual shift at that location from a spruce-pine forest 18,000 to 15,000 years ago to a juniper-pine forest by 10,000 years ago (Markgraf et al., 1984). Packrat middens in Eddy County, New Mexico, indicate that desert-grassland and desert-scrub communities predominated at lower elevations between 10,500 and 10,000 years ago (Van Devender, 1980). Soil studies indicate drier conditions at Lubbock Lake after 10,000 years ago, although marshes and small lakes persisted at the site until the construction of a dam and reservoir in 1936 (Holliday and Allen, 1987). Based on a decrease in diversity of both terrestrial and aquatic gastropod species, Pierce (1987) estimated a drop in annual precipitation at Lubbock Lake from a high of 80 cm/yr (31.5 in/yr) (nearly twice the modern level at that location of 45 cm/yr (17.7 in/yr)) 12,000 years ago to 40 cm/yr (15.7 in/yr) by 7000 years ago. Coincident with this decrease in precipitation, evidence from vole remains recovered from caves in southern New Mexico (Harris, 1988) and from plant communities throughout the Southwest (Van Devender et al., 1987) indicates a rise in summer temperatures.

By middle-Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show the southern High Plains were drier from 6500 to 4500 years ago (Holliday, 1989b) than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7000 to 5000 years ago (precipitation 0.89 times present, mean annual temperature 2.5°C higher than present), with a cooler and wetter period 1000 years ago (precipitation 1.45 times present, mean annual temperature 2.5°C lower than present) (Pierce, 1987). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period around 990 years ago (Van Devender et al., 1987). Stratigraphic work at Lake Cochise shows two mid-Holocene lake stands, one near or before 5400 years ago and one between or before 3000 to 4000 years ago, but both were relatively short-lived, and neither reached the maximum depths of the late-Pleistocene high stand that existed before 14,000 years ago (Waters, 1989).

Precipitation maxima during these Holocene wet periods were less in both magnitude and duration than those of the late Pleistocene. Enzel et al. (1989) observed comparable Holocene wet periods recorded in playa deposits in the Mojave Desert approximately 3620 and 390 years ago, and related them to short-term changes in global circulation patterns that resulted in increased winter storm activity in the region. Historical records over the last several hundred years indicate numerous lower intensity climatic fluctuations, some too short in duration to affect floral and faunal assemblages, that could also be the result of temporary changes in global circulation (Neilson, 1986). Sunspot cycles and the related changes in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world (e.g., Lamb, 1972), but the validity of the correlation is uncertain (Robock, 1979). Correlations have also been proposed between volcanic activity and climatic change (Robock, 1979; Bryson, 1989). In general, however, causes for past short-term changes are unknown. The amplitude or frequency of recurrence cannot be predicted at present. Despite this uncertainty, the past record does support the conclusion that future short-term fluctuations in the Southwest will not be as severe as the long-term climatic changes created by major ice sheets in the northern hemisphere. Full-glacial conditions remain a conservative upper limit for precipitation at the WIPP during the next 10,000 years.

Summary of Precipitation Record for the Last 30,000 Years

Based on regional paleoclimatic data and an estimated present average precipitation at the WIPP of 30 cm/yr (Hunter, 1985; Brinster, in prep.), a quantitative precipitation record for the last 30,000 years can be reconstructed (Figure V-18). This record should be interpreted with caution, because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages change gradually, and show only a limited response to climatic fluctuations that occur at frequencies higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years (Neilson, 1986). Sedimentation in lakes and playas has the potential to record higher frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation. Dry playas generally show little response to decreases in precipitation. A more complete record of precipitation would almost certainly show far more variability than that implied by the plot presented here. Specifically, Figure V-18 could fail to record abnormal precipitation lows during the Holocene; the figure could also underestimate the number of high-precipitation peaks during the same period. Precipitation variability during the Pleistocene possibly was comparable to that of the Holocene, with fluctuations occurring above and below the higher average level indicated in Figure V-18.



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3 Figure V-18. Estimated Mean Annual Precipitation at the WIPP during the Late Pleistocene and Holocene
4 (from Marietta et al., in prep.). Data references cited in text.

With these observations in mind, three significant conclusions can be drawn from the climatic record of the American SouthWest. First, maximum precipitation in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice present levels. Minimum levels may have been 90 percent of present levels. Third, short-term fluctuations in precipitation have occurred during the present, relatively dry, interglacial period, but they have not exceeded the upper limits of the glacial maximum.

Attempting a direct extrapolation of the precipitation curve of Figure V-18 into the future would be unrealistic. Too little is known about the relatively short-term behavior of global circulation patterns, and predicting the probability of a recurrence of a wetter climate such as that of approximately 1,000 years ago is impossible at present. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full-glacial conditions is highly unlikely within the next 10,000 years.

RADIONUCLIDE TRANSPORT

The Culebra Dolomite Member of the Rustler Formation is the first significant, laterally continuous, water-bearing unit above the WIPP repository. The Culebra has been identified in the site characterization as one of the most important paths for radionuclides to be transported from the repository to the accessible environment. Before transport of radionuclides in the Culebra Dolomite can be modeled, the dominant physical/chemical processes during transport must be identified and simulated.

The characteristics of the Culebra Dolomite Member were described previously (see the "Hydrogeology" section in this chapter). The significance for transport of fractures in the Culebra Dolomite Member has been examined with two hydropad tracer tests, H-3 and H-4, near the WIPP (Kelley and Pickens, 1986).

The SWIFT II computer program (Reeves et al., 1986) simulated tracer breakthrough times at H-3 and H-4. The main objective of the analysis was to conceptualize the governing physical processes for solute transport in the Culebra Dolomite Member. Given the fractured nature of the Culebra Dolomite, three possible conceptual models are a discrete-fracture model, a porous-flow model, and a dual-porosity model. Comparisons of the single- and dual-porosity assumptions in SWIFT II with observed breakthrough curves indicate that the dual-porosity model is most consistent with the observations (Kelly and Pickens, 1986).

For the H-4 tracer test, in addition to single- and dual-porosity models, a layered, porous-medium model was also included. From the SWIFT II simulations, the observed tracer-breakthrough curves were concluded to be best simulated by representing the Culebra Dolomite Member with a layered system consisting of alternating high- and low-permeability zones. The best fit was obtained for five or six high-permeability zones, although none of the fits were satisfactory, especially at longer times. This result indicates that sensitivity analyses are needed to assess how vertical resolution within important water-bearing units affects the results of transport simulations.

GEOCHEMISTRY

Radionuclide retardation during groundwater transport in the Culebra Dolomite Member of the Rustler Formation provides a potential geochemical barrier between the repository and the accessible environment. Retardation is a complex function of water chemistry, rock chemistry, and the geometry of the flow path.

Groundwater Geochemistry in the Culebra Dolomite Member

Based on available well data, four hydrochemical facies have been recognized in Culebra Dolomite Member groundwater (Figure V-19) (Lappin et al., 1989). Zone A contains a saline (about 2 to 3 molal) sodium chloride brine with a magnesium/calcium molar ratio greater than 1.2. Zone A waters occur eastward from the repository, in a region that corresponds roughly with the area of lowest transmissivity in the Culebra Dolomite. Halite is present in the lower unnamed member of the Rustler Formation throughout Zone A, and in the eastern portion of the region halite occurs in the upper members as well. Zone B is an area of dilute, calcium sulfate-rich water (ionic strength less than 0.1 molal) south of the repository. This region generally has high transmissivity in the Culebra Dolomite, and halite is absent from all members of the Rustler Formation. Zone C, located from the repository west to Nash Draw, contains waters of variable composition with low to moderate ionic strength (0.3 to 1.6 molal), with magnesium/calcium molar ratios less than 1.2. Transmissivity is variable in this region, and halite is present in the Rustler Formation only to the east, in the lower unnamed member. Salinities are highest near the eastern edge of the zone. Zone D waters, found only in two wells in Nash Draw, are anomalously saline (3 to 6 molal) and have high potassium/sodium ratios. Zone D waters are believed to be contaminated by potash mining in the region.

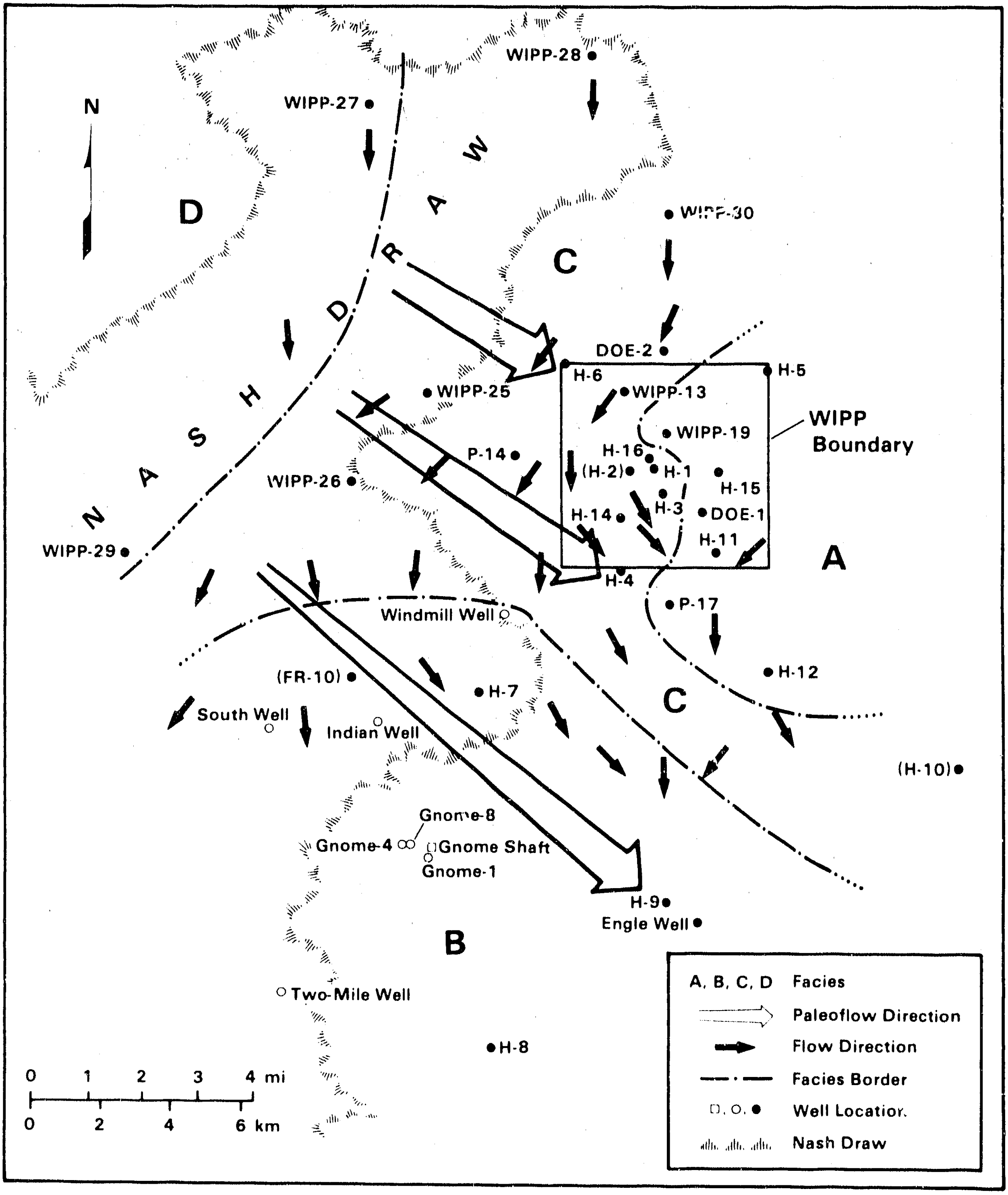

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Figure V-19. Hydrochemical Facies of the Culebra Dolomite. Compositions of waters at locations indicated by solid circles are described in Lappin et al., 1989.

The hydrochemical facies are not distributed consistently with the observed north-to-south flow of groundwater in the Culebra Dolomite. Specifically, less saline waters of Zone B are down-gradient from more saline waters in Zones A and C. Chapman (1988) suggested that direct recharge of fresh water could account for the characteristics of Zone B. As discussed previously with regard to hydrologic properties of the Culebra Dolomite, isotopic evidence provides an alternative interpretation (Lambert and Harvey, 1987; Lambert and Carter, 1987; Lappin et al., 1989). Radiocarbon dates imply that all Culebra Dolomite waters, including those of Zone B, are between 12,000 and 16,000 years old. Uranium activity ratios support the conclusion, and suggest that past groundwater flow may have been from west to east, rather than north to south. Dates are consistent with recharge associated with a wetter climate during and immediately following the last glacial maximum, approximately 18,000 years ago. Present flow could be transient, reflecting gradual drainage of the system. Regional hydrochemical facies may not have equilibrated with the modern flow regime, and instead may reflect geographic distribution of halite during a past flow regime.

On a more local scale, within Zones A and C near the repository, water chemistry may be in partial equilibrium with the modern flow regime (Siegel et al., 1990; Siegel, ed., in prep.). Modeling mass transfer reactions along flow paths shows that a large number of possible reaction sets are consistent with the observed variability in water compositions between wells H-18 and H-17 (see Figure V-8 for well locations). Modeled reactions involve evaporite minerals not found in the Culebra Dolomite, implying that the Tamarisk and lower unnamed members may contribute solutes to the system. Modeling indicates that simple mixing of various waters from the Culebra Dolomite, with or without inclusion of water from the Rustler/Salado contact zone, could not by itself account for the observed compositional variations, suggesting that clays lining fractures in the Culebra Dolomite may also play a significant role in removing or releasing solutes to the groundwater.

Radionuclide Retardation within the Culebra Dolomite Member

Distribution coefficients (K_ds), defined for a given element as the amount sorbed by a gram of rock divided by the amount in a milliliter of solution, are used in simulations of transport to calculate the partitioning of radionuclides between groundwater and rock (Lappin et al., 1989). K_ds may be determined experimentally for individual radionuclides in specific water/rock systems (e.g., Lappin et al., 1989), but because values are strongly dependent on water chemistry and rock mineralogy, experimental data cannot be extrapolated directly to a complex natural system. For performance-assessment applications, cumulative distribution functions (cdfs) for K_ds are estimated from experimental and theoretical work and used to calculate retardation factors for each radionuclide (Siegel, 1990). Retardation factors, defined as fluid velocity divided by mean radionuclide velocity, take into account pore space geometry and the thickness of clay coatings as well as K_ds to give a measure of the overall capacity of the rock to retard radionuclides. A retardation factor of 1 indicates the radionuclide migrates at the same velocity as the groundwater; higher retardation factors correspond to slower rates of migration.

For calculational expediency, Marietta et al. (1989) assumed that retardation occurred only in fractures, and ignored possible retardation by sorption and diffusion in matrix pores. Because fracture porosity is only a small fraction of the total porosity in the Culebra Dolomite, the retardation factor was low and results indicated that retardation would provide little or no barrier to radionuclide migration. Dual porosity models, in which transport and retardation are assumed to occur in both fractures and matrix pores, could provide a more realistic representation of the system. For the preliminary comparison between fracture and dual-porosity models presented in Chapter VI, cdfs for K_ds are estimated separately for matrix and fracture porosity (Siegel, 1990).

Results of ongoing research indicate that retardation of uranium by clay minerals could be substantial for systems with uranium concentrations of approximately 10^{-6} M (Siegel et al., 1990). Material scraped from fractures in core samples of the Culebra Dolomite is up to 25 percent by weight corrensite, a mixed chlorite-smectite mineral. For simplified uranium/carbonate systems, corrensite has been shown to adsorb large fractions of dissolved uranium (10^{-6} M) in a pH range (6.5 to 7.5) typical of the Culebra Dolomite (Siegel et al., 1990; Siegel, 1990). Further experimental work is necessary to determine with confidence the degree to which uranium and other radionuclides will be adsorbed by clays in the Culebra. Evidence also indicates that corrensite and iron oxyhydroxides will adsorb uranyl-carbonate and uranyl-EDTA complexes, both of which will be present in contaminated brine and which are representative of radionuclide transport by inorganic and organic complexes, respectively. Sorption by dolomite and gypsum is also expected to contribute to radionuclide retardation, but the magnitude of this contribution has yet to be quantified experimentally (Siegel, 1990).

Final cdfs for K_ds are not available. Preliminary results suggest, however, that retardation factors are orders of magnitude higher than those used in earlier simulations. For example, Marietta et al. (1989) used a retardation factor of 1.12 for transport of plutonium within fractures in the Culebra

Dolomite. Siegel (1990) suggests plutonium retardation factors for transport in fractures ranging from 76 to 676, assuming median K_d values and a range from 0.1 to 0.9 for the ratio of clay-lining thickness to fracture aperture. Comparable estimates for matrix transport range from 625 to 2000, depending on assumed values for matrix porosity. Preliminary estimates are now available for K_ds for plutonium, americium, curium, uranium, and neptunium, and all give retardation factors significantly higher than those used in previous simulations (Siegel, 1990). Further research is planned to test the assumptions used to determine these values and will provide the additional data necessary to generate cdfs suitable for use in compliance assessments.

CALIBRATING GROUNDWATER FLOW MODELS FOR THE CULEBRA DOLOMITE MEMBER

Groundwater flow models for the Culebra Dolomite Member of the Rustler Formation must provide adequate confidence for predicting flow and transport over 10,000 years. Calibration of the numerical models that approximate the conceptual model, while not a unique solution, provides a first measure of that confidence. The calibrated field represents one possible solution. For the final compliance assessment, residual uncertainty in the flow and transport parameter values must be defined in a way that accounts for all available observational information. First, the general groundwater calibration process is described. Second, the specific calibration exercise that was performed for the Culebra Dolomite Member is reviewed. Third, the performance assessment issues that will be addressed in the 1991 assessment are described.

Calibration Methodology

Calibration estimates parameter values to obtain acceptable agreement between computed and measured past behavior of the groundwater-flow system. In practice, heads are calculated and compared with observed heads. If the comparison is not judged to be acceptable, parameter values are adjusted in the direction that is believed will improve the comparison and the heads recalculated (de Marsily, 1986).

Calibration can proceed manually by trial and error until the comparison is favorable, that is, until the difference between measured and computed values is smaller than an assigned value. Parameter values that can be modified during calibration are transmissivities, leakage, storativity, recharge, discharge, and boundary conditions. These parameter values are uncertain and are subjectively changed without violating the observational data base until an acceptable solution is obtained. The solution is not unique. Different subjective judgments during the calibration process may result in different solutions. Once a solution is obtained, however, it is assumed that a greater level of confidence can be placed on the modified parameter fields than on the initial fields (de Marsily, 1986).

Automatic calibration employs a model fitting process that minimizes an objective function (for example, integral of the squares of the differences between observed and computed heads) while maximizing parameter values such as transmissivity uncertainty. Kriging, an optimal estimation technique, is frequently used to include estimates of the uncertainty of the calibration parameters. Automatic methods are state-of-the-art research areas, and few models have been calibrated successfully using such methods (de Marsily, 1986).

Calibrations based on head information can be steady or transient state. If a steady state exists in the aquifer, the observed- and calculated-head maps are compared to see if the latter fall within the desired confidence interval. If the observed-head map is drawn from kriging, the kriging error could be used to determine the confidence interval. If a steady-state fit cannot be found, a transient calibration can be based on the mean head (de Marsily, 1986).

Transient calibration should always follow a steady-state calibration. Transient calibration requires including the temporal variation of recharge and discharge within the computational domain. Temporal variation of boundary conditions can be important if natural boundaries are not selected. Otherwise, artificially imposing prescribed heads or fluxes on arbitrary boundaries can lead to significant errors that must be balanced by overmodification of parameters (for example, transmissivity within the computational domain). Varying boundary conditions can be an important part of the fitting process (de Marsily, 1986).

Because the model is numerical, computational parameters are also important. Observation wells are usually sparse and irregularly clustered within the computational domain, so variable meshes are used to examine computational parameters. Numerical behavior of the code must be well understood. Convergence studies are essential to ensure that local errors do not influence the calibration process (Roache et al., 1990).

Historically, calibrated models are used to predict the response of the existing groundwater system to perturbations such as new drilling or pumping. Such predictions require forecasting from recent records the natural recharge over the time scale of the prediction. Typically these time scales are years to decades. A transient calibration can be based on the same time scales (de Marsily, 1986).

As defined by the Standard, the regulatory time scales of interest for radioactive waste disposal are 1,000 and 10,000 years. The parameter fields obtained during calibration are uncertain. The process, whether manual or automatic, is not unique. A calibrated model can reliably predict groundwater flow for short times, but not necessarily for regulatory time scales. Uncertainty about the parameter fields derived from the calibration process must be accounted for when assessing compliance. The source of this uncertainty is not just parameter uncertainty but also modeling uncertainty. Even with automated techniques, the calibration process is subjective and not unique. Including conceptual model uncertainty is an important task for performance assessment (see Chapter III).

Existing Calibrated Fields for the Culebra Dolomite Member

An extensive calibration exercise included 10 years of data acquisition, interpretation, and simulation of the Culebra Dolomite Member (Haug et al., 1987; LaVenue et al., 1988, 1990). A steady-state calibration based on a "best estimate" of the undisturbed (pre-excavation) freshwater head distribution was performed using SWIFT II. A subsequent transient calibration (LaVenue, et al., 1990) included local hydrologic responses to four WIPP shafts, three H-2 pumping tests, H-3 convergent-flow tracer test, H-3 step drawdown test, H-3 multipad pumping test, H-4 convergent flow tracer test, WIPP-13 multipad pumping test, H-11 multipad pumping test, WIPP-14 water quality sampling, and the P-14 pumping test. These tests covered different time intervals over 8.5 years.

A manual-automatic hybrid approach was used for the transient calibration. Initial transmissivities were kriged using AKRIP (Kafritsas and Bras, 1981). Calibration parameters were pressure-boundary conditions and transmissivities. An adjoint method using GRASP II (RamaRao, in prep.) identified areas of high sensitivity on an objective function to guide modification of the transmissivity field. This approach is not automated but is significantly better than manual trial and error.

The analyst had to modify the transmissivity field in the identified sensitive zone based on judgment. In practice, modifying only the transmissivity at observation points was insufficient, or perhaps inefficient, so additional transmissivity changes were made within the high-sensitivity zones. These modifications added artificial observation points called "synthetic data" or "pilot points" (de Marsily, 1984). The parameter values assigned at the pilot points were determined from the analyst's experience. The calibration proceeded iteratively until acceptable agreement with the observed heads was obtained. Because the SWIFT II computational domain is larger than the capability of the GRASP II code, the calibration proceeded through subdomains with pilot points added sequentially. Because changing the sequence of calculations, subdomain boundaries, mesh size, and so on, could change the resulting parameter fields, the calibration is not unique.

The steady-state transmissivity field with superimposed observation wells and pilot points reveals a high-transmissivity zone extending to the south of the WIPP-controlled area (Figure V-20). Flow and particle transport are towards the south through this high-transmissivity feature. The feature is flanked by H-17, P-17, and H-4, but only pilot points lie within the feature (Figure V-20) (LaVenue et al., 1990).

The transient calibration used the steady-state fields as initial conditions. Reducing the differences between calculated and observed heads as each new test was added to the time record required systematic addition of more pilot points until the transient calibration covered the 8.5-year record. The final calibration included about 40 observation wells and 44 pilot points (Figure V-21) (LaVenue et al., 1990).

The difference between the steady-state and transient fields is primarily a northward extension of the high-transmissivity zone. Some anomalies in the final comparison persist around the four shafts, but these can be explained by additional leakage into the shafts (LaVenue et al., 1990). The calibrated field is most sensitive to calibration parameters, boundary conditions, and transmissivities in the northwest quadrant of the domain. Again, groundwater and particle travel paths from the WIPP waste panels are towards the south (LaVenue et al., 1990).

Performance Assessment Approach

The existing calibrated fields are based on 8.5 years of tests. Performance assessments must calculate future states for 10,000 years to assess compliance. The calibrated fields used for assessments must include parameter and conceptual-model uncertainty to satisfy regulatory intent. How to handle both of these sources of uncertainty is an open question. For calculational expedience, a zone approach (see Appendix C) used earlier has been retained for the 1990 preliminary assessment (Bonano et al., 1989; Marietta et al, 1989). Zones do not adequately handle either source of uncertainty and are used here as an interim approach.

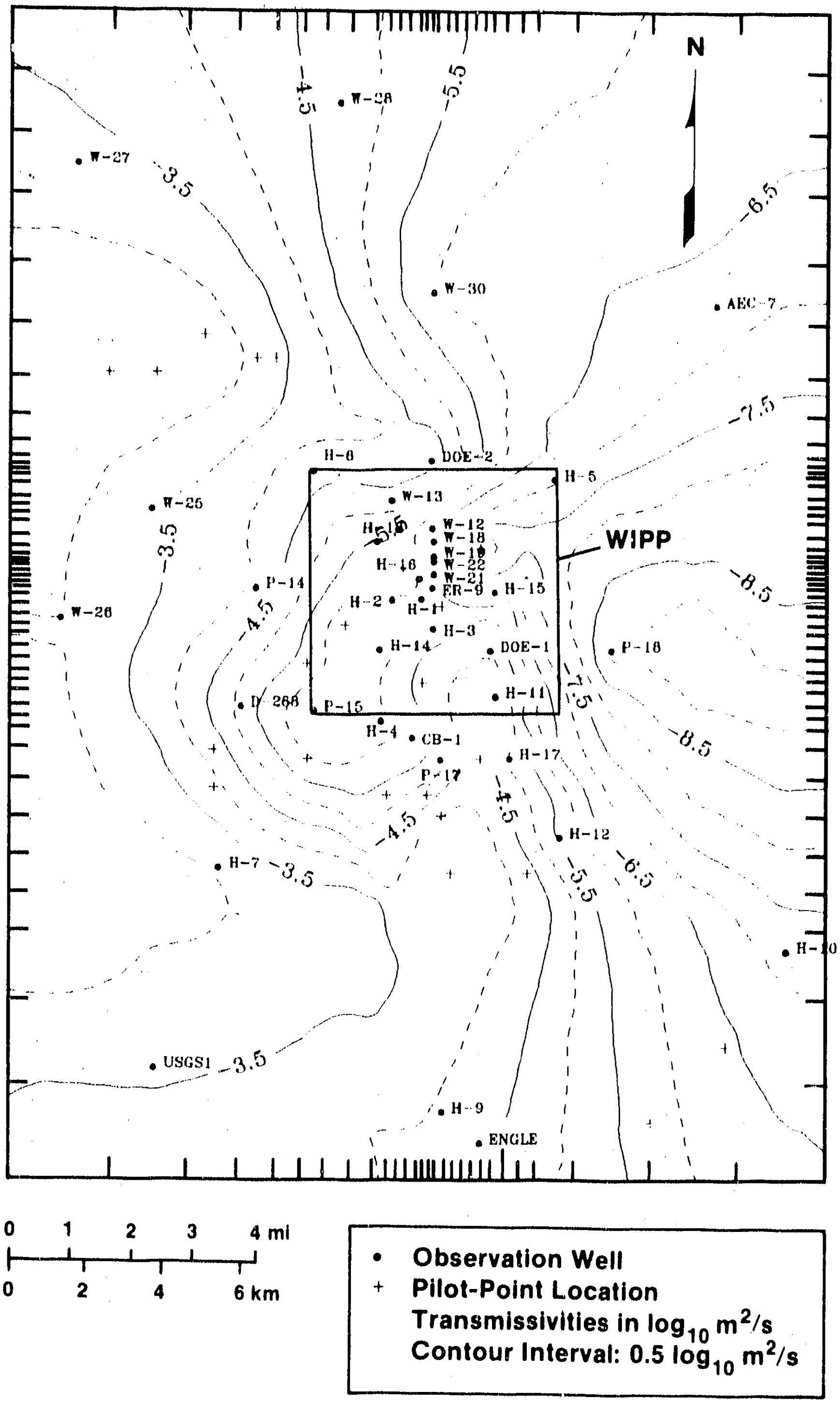

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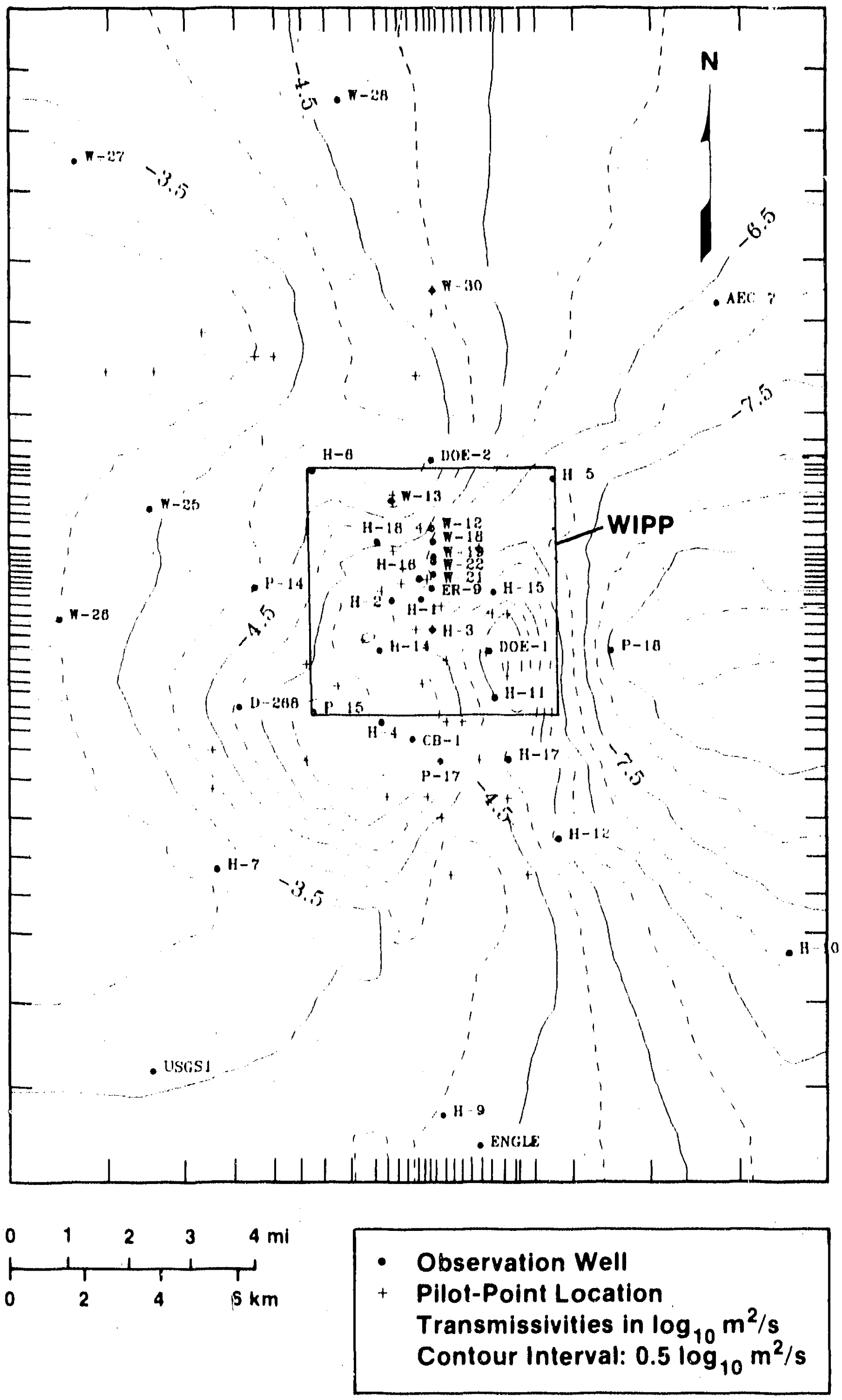
Figure V-20. The Steady-State Calibrated Log_{10} Transmissivities in Culebra Dolomite (LaVenue, et al., 1990).



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3 Figure V-21. The Transient Calibrated Log_{10} Transmissivities in Culebra Dolomite (LaVenue, et al., 1990).

The objective for the final performance assessment is to generate Monte-Carlo simulations of flow and transport parameter values that display the residual uncertainty when all available observational information is taken into account. The geostatistical technique of conditional simulation (Matheron, 1971, 1975) is available in CAMCON and will be used in the 1991 assessment. Conditioning should be done on measured parameter values, regional geological understanding, and hydrologic measurements used in the calibration. Measured parameter conditioning will be done with kriging and turning band methods. Regional geological conditioning will be included in the kriging by cokriging or including trends in the drift, that is, generalized covariances or prescribed external drift. Hydrologic measurement conditioning is related to the formulation of the inverse problem solution (transmissivity fields derived from the calibration).

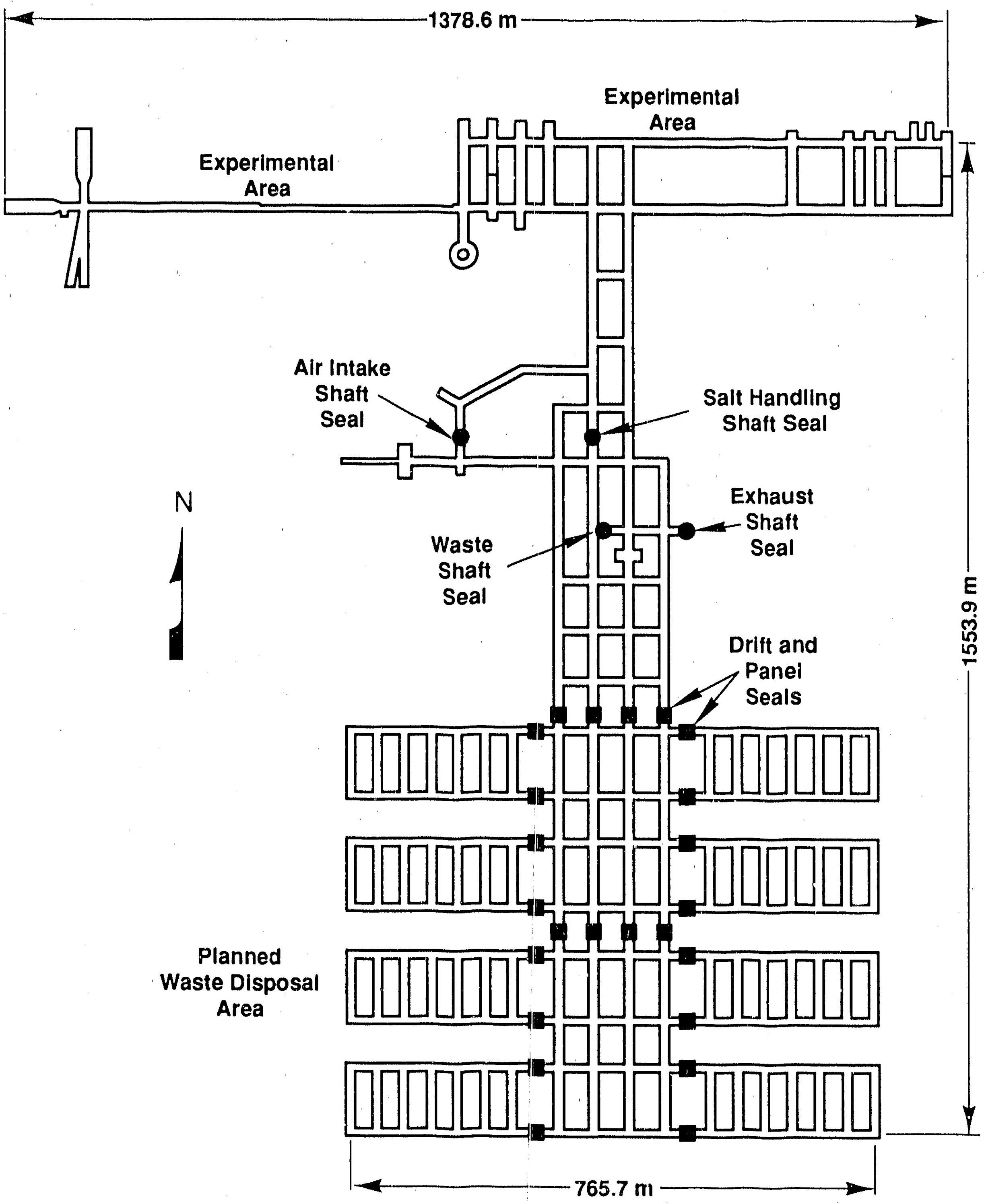
Sensitivity analyses on the inverse model will be carried out after a final transmissivity field is calculated to determine residual uncertainty. Because the solution to the inverse problem relies on pilot points, the difficult step of determining the uncertainty associated with pilot point values must be resolved. This uncertainty is clearly not the kriging error, which assumes that the parameter values at the pilot points are certain. Other approaches that do not use pilot points are possible. The question of uncertainty in the transmissivity field will be examined, alternative methods compared, and one (or more) approaches will be adopted for use in the 1991 preliminary performance assessment.

Repository/Shaft System

The repository/shaft module of the compliance assessment system includes flow and transport within the underground workings at the repository horizon and within various shafts and boreholes that connect the underground workings with overlying formations. Figure V-22 shows a plan view of the repository design. The waste-disposal rooms occupy the southern end of the mined horizon. All rooms, drifts, and shafts will be backfilled when the repository is closed.

OVERVIEW

A model of the complex repository/shaft system must be included in the compliance assessment system (i.e., in CAMCON) for assessing performance and carrying out uncertainty and sensitivity analyses. This model includes the source term and all important processes that bear upon transport of radionuclides from the storage rooms. For the undisturbed scenario, the



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3 Figure V-22. Plan View of Storage Horizon Showing Shaft, Drift, and Panel Seal Locations (after
4 Stormont, 1988).

modeling problem is to predict the transport of radionuclides from the rooms through the entire repository/shaft system to overlying fluid-bearing zones, such as the Culebra Dolomite Member of the Rustler Formation. A source within the hydrology model for this member is specified and a coupled fluid-flow/transport simulation continued to the boundary between the controlled area and the accessible environment. A similar separation between the repository and the Culebra is modeled for analyzing the human intrusion scenarios.

An intrusion borehole that penetrates a storage room serves as a possible flow connection with overlying or underlying formations. Flow and transport through this connection can be described, and sources characterized within fluid-bearing zones that are appropriate for each human-intrusion event. In this case, the repository/shaft model impacts the analysis only through the waste-storage room. The degree of consolidation of the room and its contents at the time of intrusion help define the source term for the simulation.

CAMCON provides an efficient, readily available tool for modularizing components within the respository/shaft system. The design of the repository and shafts divides into components that are connected but can be treated separately. Each component includes the various processes determined to be important for the transport problem. These processes and important parameters are selected on the basis of sensitivity analyses performed on the repository/shaft systems model.

Construction of a complete repository/shaft module for CAMCON is complicated because of the wide range of model types needed to analyze different processes that influence repository performance. Many of these models can also be used for consequence modeling, and would normally be used during compliance assessment. Because models used for design range from simple analytical models to complex finite-element models, a reasonable match of component models and data is required for systems studies. Construction of a compliance assessment module provides a mechanism for feedback to repository design through sensitivity analyses that are used to match modeling components and data.

The component of the repository/shaft systems model that represents a single room incorporates many phenomena. Predicting the final state of the room is the main objective, but predicting impacts of human intrusion is equally important. To predict the room's final state, the following factors are being considered during model development, even though some of them may not be important or even appear in the final model (Table V-1).

TABLE V-1. FACTORS POTENTIALLY IMPORTANT FOR MODELING THE ROOM

- Creep closure of the salt
- Brine inflow from the Salado Formation
- Structural response of the backfill mix
- Structural response of the waste containers and contents
- Inventory and waste categories
- Room and brine chemistry
- Gases generated by microbiological, radiolytic, and corrosive decomposition of waste materials
- Brine and gas interactions with the backfill mix
- Gas interactions with the Salado Formation
- Brine and gas interaction with MB139 and overlying anhydrite layers
- Radionuclide solubilities in the room environment
- Effect of intruding drilling fluids
- Effect of injected pressurized brines from intrusion boreholes

Sources: Tyler et al., 1988; Lappin et al., 1989; Bertram-Howery and Hunter, 1989a

For the human intrusion scenarios, the room is directly connected to overlying fluid-bearing zones by one or more boreholes. Concentrations of radionuclides in the room as a function of time following these intrusions must be estimated to describe the rate of radionuclide migration to overlying water-bearing units. Preliminary calculations (Lappin et al., 1989; Marietta et al., 1989) used solubility-limited source terms that included the volume of an entire panel. Sensitivity analyses (Marietta et al., 1989, Appendix A; Rechard et al., 1989) assessed this assumption to refine the volume of waste accessible to an intrusion borehole and to account for brine flow rate through the waste panel. For the undisturbed scenario, transport through panel seals (Figure V-22) and the MB139 seal (Figure IV-3) must be modeled (Table V-2).

TABLE V-2. FACTORS TO BE CONSIDERED IN THE PANEL-SEAL COMPONENT

Consolidation of seal materials

Saturation effects on consolidation

Gas effects on seal consolidation and saturation

Pressure effects on seal materials after pressurized brine injection for an intrusion borehole

Pressure driven flow and transport through seals, along seal/host rock interface, and through the disturbed rock zone

Radionuclide retardation in brine-saturated seals and host rock in the saturated brine environment

Sources: Tyler et al., 1988; Lappin et al., 1989; Bertram-Howery and Hunter, 1989a

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The properties of a single panel seal are considered during sensitivity studies and seal design. The eventual module must account for the system of panel seals and backfilled drifts. The room/panel seal connection will be integrated and scaled into a network that combines the effect of many rooms, drifts, and seals into one module for systems simulations. This network represents everything to the south of the northernmost panel seals (Figure V-22).

The anhydrite-clay marker bed MB139 is an important parallel path for radionuclide transport to the shafts. MB139 will be sealed under all panel seals. Portions of MB139 under the backfilled drifts also will be included in the panel-seal module (Figure IV-3).

MB139 and the system of drifts from the northernmost panel seals to the bottoms of the various shafts (Figure V-22) form the drift component. The features of this component that must be considered in developing a drift system module are similar to features of the panel-seals module (Table V-3). Backfill material in this part of the drifts may be identical to panel-seal material (i.e., salt blocks), but is more likely to be crushed salt.

The shaft/seal component is another separate system of seals with stiff structural members that maintain seal-material integrity during consolidation. This component is represented by a single module (Table V-4). The seal material in the lower seal system was selected to reproduce the

TABLE V-3. FACTORS TO BE CONSIDERED IN THE DRIFT/MB139 COMPONENT

- Backfill consolidation
- Reconsolidation of the disturbed rock zone
- Saturation effects on consolidation
- Radionuclide retardation in host rock and backfill materials
- Brine and gas interaction with host rock and backfill materials
- Brine and gas interaction with MB139
- Radionuclide retardation in MB139 and backfill materials

Sources: Tyler et al., 1988; Lappin et al., 1989; Bertram-Howery and Hunter, 1989a

TABLE V-4. FACTORS TO BE CONSIDERED FOR THE SHAFT/SEAL COMPONENT

- Consolidation of seal materials
- Saturation of the shaft/seal system from host rock, overlying water-bearing units, or pressurized Castile Formation brine
- Radionuclide retardation by host rock and seal materials
- Flow and transport through seal materials, along the host rock/shaft interface, and through the disturbed rock zone

Sources: Tyler et al., 1988; Lappin et al., 1989; Bertram-Howery and Hunter, 1989a

desirable natural-barrier features of the Salado Formation. The seal material and design in the upper seal system was selected to prevent fluid seepage from the overlying fluid-bearing zones. Material for stiff members was selected to maintain system integrity until final consolidation, which will occur by lateral rather than vertical salt creep, is complete.

Two fluid-flow applications of the shaft/seal component are necessary for compliance assessment. First, upward transport of radionuclides through the seal system to overlying water-bearing units must be considered for undisturbed performance analyses. Second, fluid seepage downward is a possible mechanism for repository saturation and should be simulated as part of design sensitivity analyses.

The bottom of the shaft will be separated from the drift by a concrete seal that is included in the shaft/seal system. Stiff-member materials such as the concrete layer at the bottom of the shaft are not designed to survive in the brine environment for more than a hundred years after repository closure. The connection between the drift and shaft modules, therefore, is only a transition from drift backfill to shaft-seal material. A sensitivity analysis to assess the importance of drift-backfill materials within the overall system will guide materials selection. Similarly, the shaft seal system above the repository horizon can be modeled as a seal consisting only of consolidated salt because the degradation time for the stiff member is short compared to the 10,000-year Containment Requirements.

The assembly of these components into a systems model requires individual component and system sensitivity analyses to identify important parameters and processes. Detailed complex models with finite-element structural-analysis computer programs are used where data are extensive (e.g., room closure). Simplified analytical or even network flow models may be used where data are sparse (e.g., transport through shaft seals). Even though highly detailed, finite-element and finite-difference fluid-flow programs are available, model selection must be commensurate with supporting data and the importance of the module to the performance of the repository.

Many of the important phenomena must be considered in a coupled mode. Consolidation with the back-pressure response of interstitial brines and simultaneous gas generation is one example. The final room module could be a set of simplified empirical calculations using data derived from complex-model simulations, analytical solutions, and measurements. Empirical data-fitting will be based on a systematic sensitivity analysis of the overall system.

WASTE PANEL MODELING

The disposal-room characterization program studies how TRU waste and backfill mixtures interact in a waste room as the mixture consolidates in response to creep of the surrounding salt. The interaction of waste and containers, backfill mixtures, brine, and gases during closure are being studied through laboratory tests, small- and large-scale field experiments for different engineered modifications, and sensitivity analyses to assess performance and safety. A major aspect of room modeling is coupling individual components into a model that allows room conditions to be estimated as a function of time. For WIPP performance assessment, the state of the room when intersected by a borehole and the transient response following that event are important for predicting radionuclide migration away from the room.

Closure, Flow, and Room/Waste Interactions

When the repository is decommissioned, waste-disposal panels, access drifts, and the experimental area will be backfilled, and the drifts and shafts will be sealed. Special grout seals will be placed within MB139 directly beneath the panel seals, preventing fluid flow in fractures formed during excavation and subsequent salt creep. Free brine initially will not be present within the disposal area, and void space above the backfilled waste will be air-filled (Figure V-23a). Brine seepage from the Salado Formation will have filled fractures in MB139 beneath the disposal area (Lappin et al., 1989; Rechard et al., 1990a).

Following decommissioning, salt creep will begin to close the repository (Figure V-23b). In the absence of elevated gas pressures within the repository, modeling of salt creep indicates that consolidation of the waste could be largely complete within 100 years (Tyler et al., 1988; Munson et al., 1989a, 1989b). Brine will seep into the disposal area from the surrounding salt, however, and gas will begin to be generated in the humid environment by corrosion of metals, radiolysis of brine, and microbial decomposition of organic material. Some gas will disperse into the surrounding anhydrite layers. Continued gas generation could increase pressure within the repository sufficiently to reverse brine inflow and partially or completely desaturate the waste-disposal area (Figure V-23c). High pressure may also halt and partially reverse closure by salt creep. In the undisturbed final state, the disposal area could be incompletely consolidated and gas-filled rather than brine-filled (Figure V-23d).

Predicting conditions within the disposal area at any particular time is a difficult task. The problem can be examined qualitatively by considering interactions of the controlling processes. All processes are linked, and all are rate- and time-dependent. For example, creep closure will be, in part, a function of pressure within the repository. Pressure will be in turn a function of the amount of gas generated and the volume available within the repository and the surrounding Salado Formation for gas storage. Gas storage volume will be a function of closure rate and time, with storage volume decreasing as consolidation continues. Time and rate of gas generation, therefore, will strongly influence repository pressurization and closure. Gas-generation rates will be dependent on specific reaction rates and the availability of reactants, including water. Some water can be generated by microbial activity (Brush and Anderson, 1988a). Additional water will be provided by brine inflow, which, in the absence of a final mechanistic model, is assumed to occur according to two-phase Darcy flow. Other possibilities

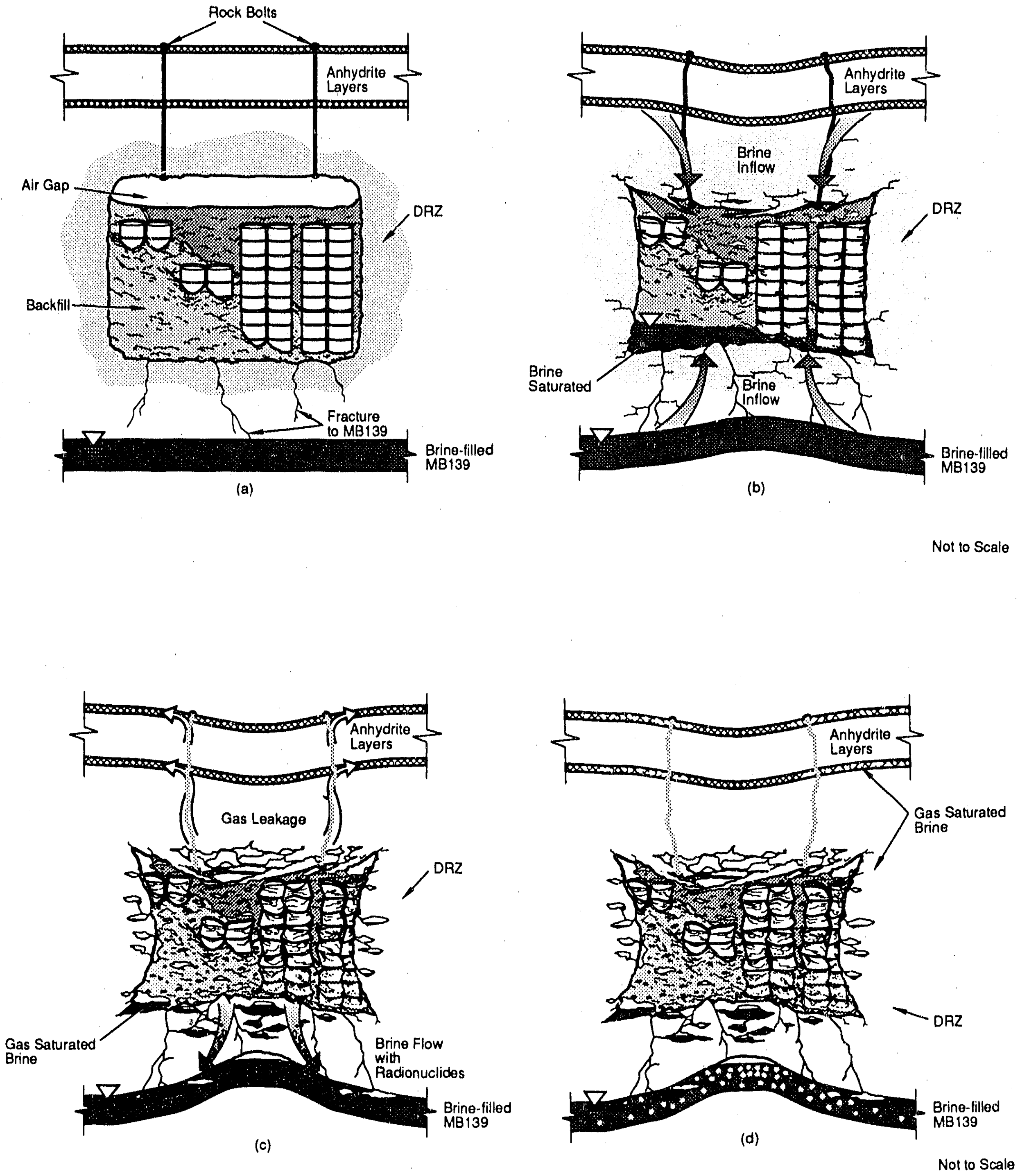

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Figure V-23. Hypothesized Episodes in Disposal Area Leading to Undisturbed Conditions. This drawing shows (a) initial conditions after decommissioning and (b) room creep closure and brine inflow (c) gas generation, brine outflow, and room expansion, and (d) undisturbed conditions with gas-filled room surrounded by gas-satured brine (Rechard et al., 1990a).

are being investigated. Whatever model is used, brine inflow will depend in large part on repository pressure, so that some gas-generation reactions could be partially self-buffering.

Responses of the disposal system to human intrusion are equally complicated. Consequences will depend on the time of intrusion, the degree to which the repository has closed, and the amount of gas generated. If intrusion occurs into a fully pressurized, dry, and partially unconsolidated waste-disposal area, venting of gas up the borehole will permit brine to resaturate available void space (Figure V-24a,b). Following eventual deterioration of borehole plugs, brine may flow from the disposal area into the borehole, transporting radionuclides upward to the Culebra Dolomite. Upward flow from a pressurized brine pocket in the Castile Formation may contribute to flow and radionuclide transport (Figure V-24c).

Performance assessments must model the consequences of intrusion as a function of conditions within the waste-disposal area. For example, radionuclide transport will depend in part on the rate of brine flow through the waste, which in turn will be a function of brine availability and waste permeability. Time- and pressure-dependent consolidation by creep closure will be a major factor in determining waste permeability. Models and the database needed to describe conditions within the waste-disposal area in detail are still incomplete. Present interpretations are based on simplifying assumptions that will be modified as research progresses.

THE RADIONUCLIDE SOURCE

Current performance assessment calculations use an initial waste inventory that includes both CH and RH waste (Table V-5). The CH-waste inventory is that of Lappin et al. (1989), and is based on input to the 1987 Integrated Data Base (U.S. DOE, 1987b). The inventory includes estimates of both existing waste and waste that will be generated by the year 2013. The CH-waste inventory is somewhat smaller than that reported in the FSEIS (U.S. DOE 1990b), where estimated quantities of CH waste were scaled up to 10.7 percent by volume to match the design capacity of the facility. The RH-waste inventory is as predicted in early September, 1990. Both inventories will be updated when appropriate, and results of performance assessment calculations will change accordingly.

Current simulations of intrusion events assume that brine flow occurs throughout an entire waste panel, making radionuclides from both RH- and CH-waste available for transport in solution. Because RH waste will occupy a

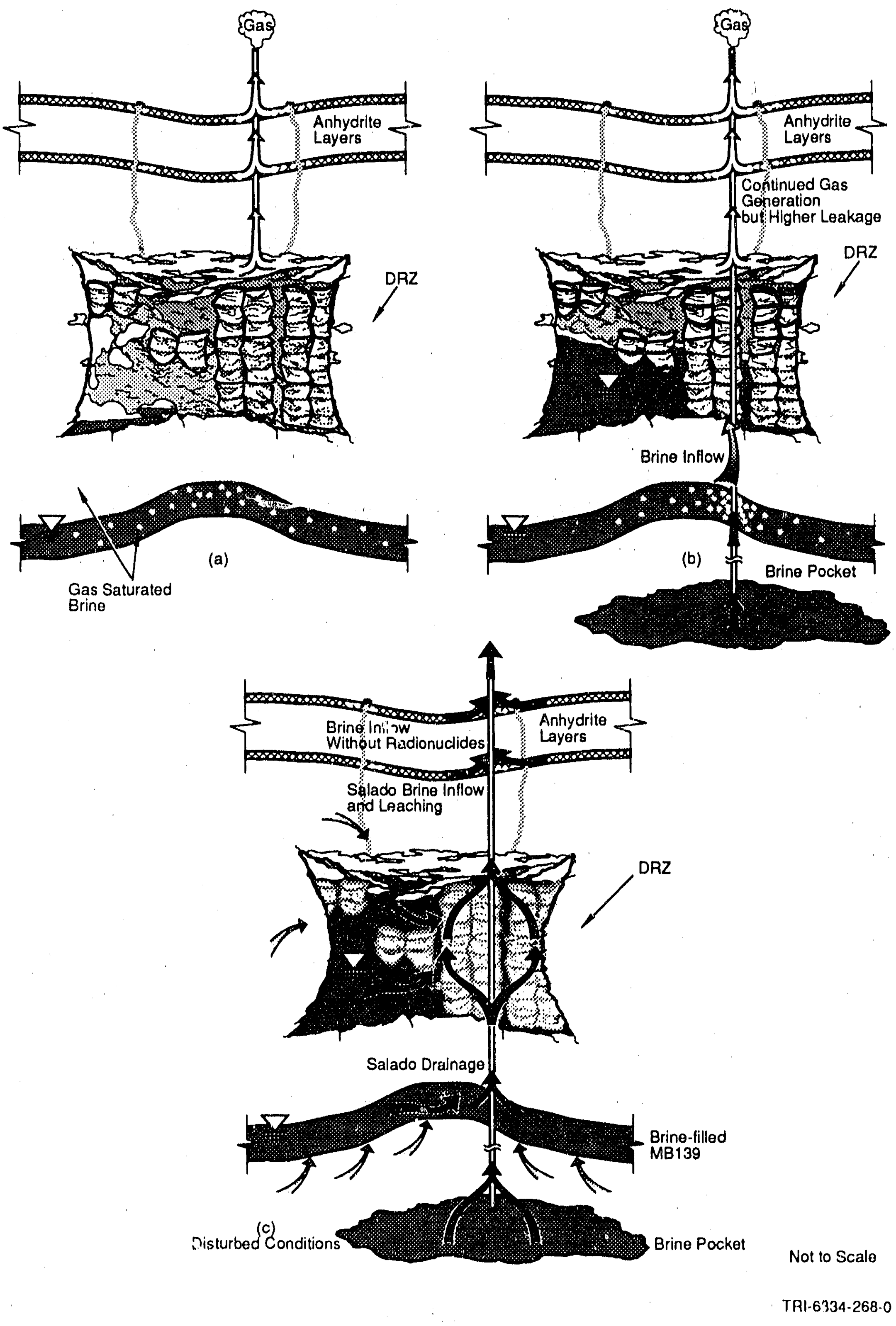

Figure V-24. Hypothesized Episodes in Disposal Area After Human Intrusion. This drawing shows (a) initial room gas depressurization when penetrated by exploratory borehole, (b) final gas and brine depressurization as borehole seals degrade, and (c) brine flow through borehole to Culebra Dolomite (Rechard et al., 1990a).

TABLE V-5. INITIAL WASTE INVENTORY

Radionuclide	Half-life(yr)	Curies	Grams
	CH-Waste[a]		
Th-232	1.41×10^{10}	2.7×10^{-1}	2.5×10^{6}
U-233	1.59×10^{5}	7.7×10^{3}	8.0×10^{5}
U-235	7.04×10^{8}	3.7×10^{-1}	1.7×10^{5}
U-238	4.47×10^{9}	1.5	4.4×10^{6}
Np-237	2.14×10^{6}	8.0	1.1×10^{4}
Pu-238	8.77×10^{1}	3.9×10^{6}	2.3×10^{5}
Pu-239	2.41×10^{4}	4.2×10^{5}	6.8×10^{6}
Pu-240	6.54×10^{3}	1.0×10^{5}	4.6×10^{5}
Pu-241	1.44×10^{1}	4.1×10^{6}	4.0×10^{4}
Pu-242	3.76×10^{5}	1.8×10^{1}	4.6×10^{3}
Am-241	4.32×10^{2}	6.3×10^{5}	1.8×10^{5}
Cm-244	1.81×10^{1}	1.3×10^{4}	1.6×10^{2}
Cf-252	2.64	2.0×10^{3}	2.8×10^{1}
	RH-Waste[b]		
Sr-90	2.91×10^{1}	2.8×10^{5}	2.0×10^{3}
Cs-137	3.00×10^{1}	3.3×10^{5}	3.8×10^{3}
Pm-147	2.62	3.2×10^{5}	3.4×10^{2}
Th-232	1.41×10^{10}	2.3×10^{-3}	2.1×10^{4}
U-233	1.59×10^{5}	2.8×10^{1}	3.0×10^{3}
U-235	7.04×10^{8}	1.2×10^{-2}	5.7×10^{3}
U-238	4.47×10^{9}	7.8×10^{-2}	2.3×10^{5}
Np-237	2.14×10^{6}	7.0×10^{-1}	9.9×10^{2}
Pu-238	8.77×10^{1}	5.1×10^{2}	3.0×10^{1}
Pu-239	2.41×10^{4}	1.4×10^{3}	2.3×10^{4}
Pu-240	6.54×10^{3}	2.9×10^{2}	1.3×10^{3}
Pu-241	1.44×10^{1}	1.3×10^{4}	1.3×10^{2}
Pu-242	3.76×10^{5}	3.3×10^{-3}	8.4×10^{-1}
Am-241	4.32×10^{2}	1.3×10^{3}	3.8×10^{2}
Cm-244	1.81×10^{1}	8.8×10^{3}	1.1×10^{2}
Cf-252	2.64	2.4×10^{3}	4.4
	Additional Decay Products		
U-234	2.44×10^{5}	0	0
U-236	2.34×10^{7}	0	0
Th-229	7.43×10^{3}	0	0
Th-230	7.70×10^{4}	0	0
Ra-226	1.60×10^{3}	0	0
Pb-210	2.23×10^{1}	0	0

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[a] Lappin et al., 1989, Table 4-2a; see also Rechard et al., 1990b.

[b] Rechard et al., 1990b. RH-waste is not included in inventory for simulation of direct removal as cuttings and eroded material.

very small area relative to CH waste, simulations of direct transport of waste to the ground surface as cuttings and eroded material use only the CH-waste inventory. Lower probability intrusions directly through RH waste will be examined in future performance assessments.

Radioactive decay within the repository is simulated with a complete set of decay chains. Transport, which begins when radionuclides leave the repository, is simulated using a simplified set of four decay chains that omit radionuclides with short half-lives, low radiological toxicity, or low activities (Table V-6) (Lappin et al., 1989). The radionuclide inventory for transport calculations is a function of the initial inventory, simulated decay within the repository, and the time at which transport begins (that is, the time of intrusion).

Transport analyses do not incorporate gaseous transport of volatile radionuclides (Lappin et al., 1989). The only radioactive gas expected in the repository is radon-222, created by the decay of radium-226. Decay of thorium-230 will cause the quantity of radium-226 to increase throughout the 10,000-year regulatory period (see simplified decay chain, Table V-6). Radon-226, with a short half-life of 3.8 days, will exist in secular equilibrium with radium-226; the activity of radon-226 throughout the 10,000-year period will be insignificantly small.

TABLE V-6. SIMPLIFIED RADIONUCLIDE CHAINS FOR TRANSPORT CALCULATIONS

(1) Pu-240 → U-236

(2) Am-241 → Np-237 → U-233 → Th-229

(3) Pu-238 → U-234 → Th-230 → Ra-226 → Pb-210

(4) Pu-239

The inventory to be used for the above four chains is listed in Table V-5.
Source: Lappin et al., 1989, Table 4-3

Estimates of radionuclide solubilities in brine are still preliminary, although research is in progress to quantify the speciation of plutonium, americium, thorium, and uranium in concentrated solutions (Brush and Lappin, 1990). Solubilities will be dependent on Eh, pH, and concentrations of organic and inorganic ligands. Values for these parameters will vary as brine reacts with waste. Preliminary calculations assume an arbitrarily chosen log-uniform distribution of radionuclide concentrations of 10^{-9} to 10^{-3} M in disposal-area brine (Lappin et al., 1989; Brush and Anderson, 1989). For most radionuclides, the dissolved quantity is limited by brine flow through the waste. For some radionuclides with either high solubilities or low inventories, inventory limits total release.

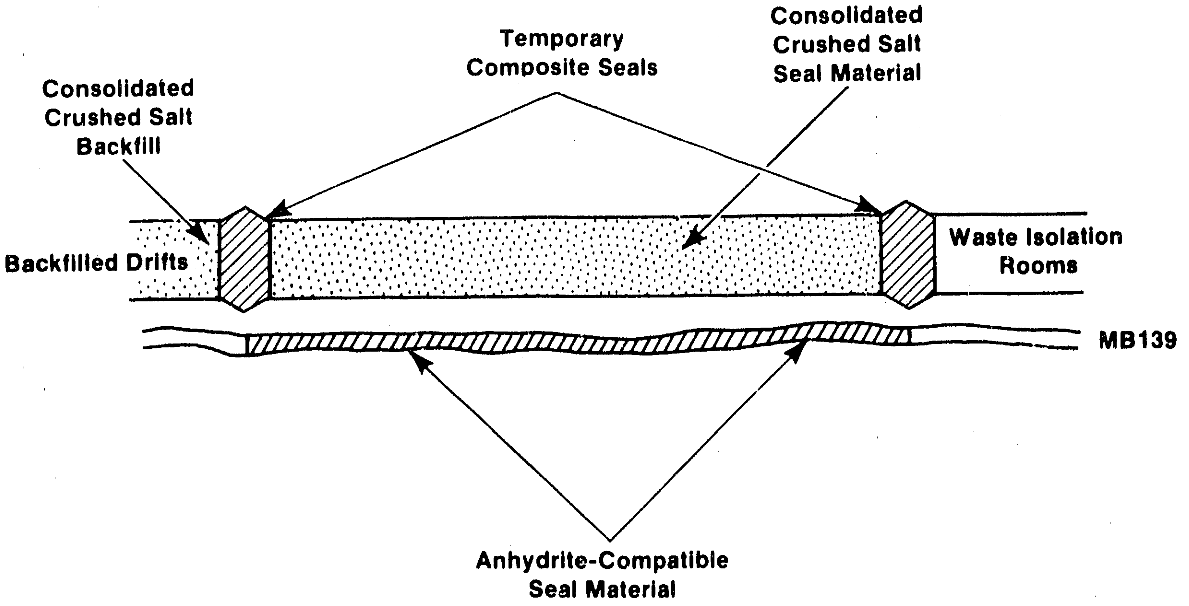
PANEL-SEAL MODELING

Panel seals isolate disposal rooms from the remainder of the repository (Figure V-22). A number of factors must be integrated to complete the conceptual-seal design (Figure V-25). Analyses of brine inflow from the host rock, gas outflow from the waste panels, consolidation of seal materials, creep closure of the host rock, disturbed zone formation and closure, and stress must be applied to panel-seal design and modeling. Structural analysis and fluid-flow programs developed for room design are used to analyze performance of seal components.

Various empirical, analytical, or numerical programs must be merged and may be simplified for use as a panel-seal module. Significant differences exist in model setup. Seal geometry requires different meshes to represent seal shape and material differences. Analysis of seal performance requires simulating three possible flow paths: flow through seal materials, flow along the interface between seal materials and the host rock, and flow through the host rock and interbeds including the disturbed rock zone. Panel-seal models must simulate flow and transport along these three pathways. A pathway determined to be unimportant by sensitivity studies will not be included. Final modules for room/panel seals must account for the full assemblage of rooms and seals (Figure V-22), so a network modeling approach may be the most reasonable choice. The network model will require that individual components of the system be fully modeled.

Seal-Material Consolidation Modeling

These studies use the same models for constitutive and structural analyses that are used in modeling backfill-mix consolidation and closure for the room. Crushed and block salt without additives must be analysed to determine the final degree of consolidation of the system. The sensitivity of consolidation of crushed-salt seal components to brine inflow, gas outflow, creep closure, initial density, and other parameters (Nowak and Stormont, 1987), has been initially determined. Seals include layers, probably consisting of bentonite and concrete, that resist creep closure. Layering must be included in structural analyses. Seal designs include



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3 Figure V-25. Schematic Design of a WIPP Panel Seal (Lappin et al., 1989).

over-excavation of the drift, which develops stress concentrations at corners and could cause the host rock to fracture. These effects must be modeled using variable meshes and fracture models.

Brine-Inflow and Gas-Outflow Modeling

Consideration of brine inflow from the host rock and gas outflow from the waste panels is important in assessing panel-seal performance during consolidation, because brine and gas may create backpressure that retards closure. As is the case with the room, predicting the final degree to which panel seals consolidate requires coupling two-phase flow and creep-closure models. Again, the models (e.g., Nowak et al., 1988) applied to the room can be applied to different materials and geometries of panel seals.

Disturbed Rock Zone Modeling

Modeling flow through the disturbed rock zone (DRZ) is particularly important for panel and shaft seals. Flow and transport through fractures of the DRZ could possibly circumvent seal materials. The fracture pattern around panel seals will probably be complex and anisotropic after overexcavation of the drift. This possible pathway can be assessed by simulating pressure-driven flow through the DRZ, host rock, and interbeds. A pressure gradient may exist across panel seals in the final consolidation state. As discussed in the human-intrusion scenario, injection of Castile Formation brines into the room could also result in such a pressure gradient. Seal performance under such hypothetical conditions must be assessed.

Tracer-gas studies (Stormont et al., 1987; Peterson et al., 1987) have been conducted to estimate fracture continuity and apertures in MB139. These studies indicated connection between the excavations and MB139 through the fractured salt. Further studies are underway to analyze the effects of the DRZ (i.e., its fracture-induced porosity) on hydrologic properties. Simulating fracture flow and transport through the host rock requires a flow program with a fracture model. First, formation of the DRZ in response to the excavations of the drifts, rooms, and seals must be described. A description of the processes that form the DRZ and the way in which it will respond during closure (e.g., to what extent the fractures will heal) can be developed by integrating various fracture data. A predictive capability for simulating fracturing and fracture closure is being developed from this conceptual model. If feasible, a fracture model will serve as a constitutive model and be included as part of the computational scheme within structural analysis programs. If the fracture pattern is fixed, fractures can be included in flow programs. Otherwise, the fracture model must be coupled with a deformation code so the changing fracture pattern can be predicted.

Then fluid flow and its backpressure effects can be included. The pore space within the DRZ has been desaturated (Borns and Stormont, 1988; 1989) by microfracturing and mine ventilation. Because of this increased pore volume, the DRZ's ability to accept fluids, both brine and gas, is enhanced. Programs for simulating such coupled processes do not exist although, in principle, the programs can be assembled. For developing a module commensurate with the relative importance of panel seals within the repository/shaft system, a fairly simple network model relying on two-phase Darcy flow and a dual porosity approximation for transport is a reasonable first step.

Flow and Transport Modeling

The undisturbed-scenario analysis requires simulating two-phase flow and transport through the repository/shaft system to overlying water-bearing units (e.g., the Culebra Dolomite Member). Room consolidation or gas generation could cause pressure within the disposal room to exceed hydrostatic pressure. Transport through, along, and/or around panel-seal materials must be modeled. To handle all scenarios, equations (including retardation and fracture flow) for radionuclide transport along the three possible flow pathways must be solved. Because network models only solve one-dimensional equations along preassigned pathways for fixed-fluid fields, more detailed, multi-dimensional modeling is required to justify the use of these simplified models in the uncertainty analyses. The 1991 assessment will use at least two-dimensional, one- and two-phase flow simulations of the repository/shaft system with panel seals included as changes in material properties.

Panel Seal and Room Assemblage

Once transport past a single panel seal from a single panel can be adequately estimated by room-performance and panel-seal modules, the effect of all storage rooms and drifts behind the northernmost panel seals can be estimated by assembling individual component networks into a multicomponent network. The diffusive and perhaps advective fluxes of radionuclides across the northern panel seals are required for interfacing with the drift module. A multipath, network model could be used, although the results would be limited by all the disadvantages of using simplified numerics and physics. The applied network program would require careful benchmarking against more complete, verified, dynamical programs on test problems designed for the WIPP repository geometry. A more straightforward approach could be to use the latter dynamical programs and take advantage of CAMCON's flexibility for handling domain decomposition. An approach will be selected.

DRIFT MODELING

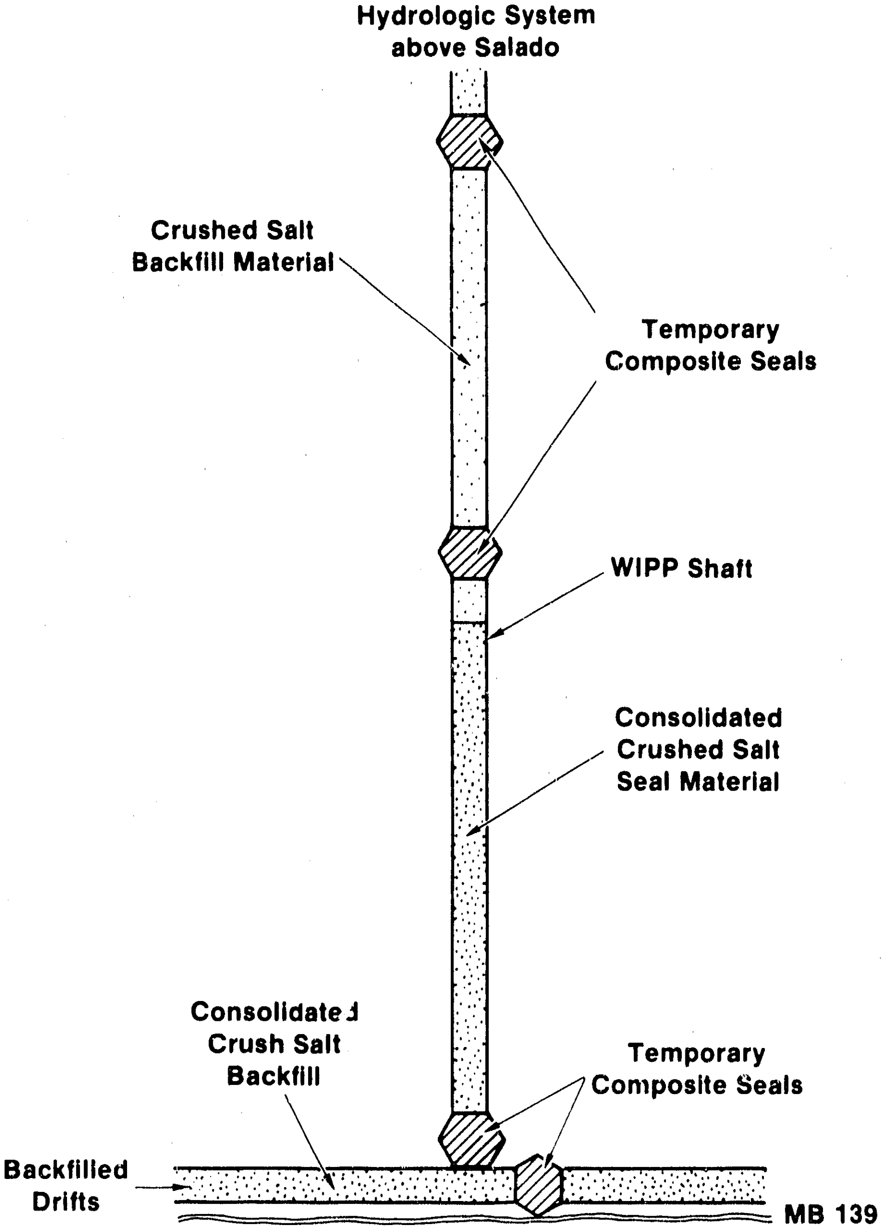
Drift modeling will simulate flow and transport from the northernmost panel seals to the concrete bases of the shafts (Figure V-26). Two-phase Darcy flow and transport through the host rock underlying MB139 and other interbeds will be included. Drifts may contain backfill consisting of salt or salt mixed with other materials. Final selection of backfill for these drifts depends on their role in overall system performance as estimated by the CAMCON system. The drift module is another application of the creep-closure, brine-inflow, gas-outflow, and transport programs used for the room/panel-seal modules, using somewhat different geometry and materials. Output of the drift module is radionuclide flux into the bottom of the shaft-seal material. Because concrete is not designed to last beyond a hundred years, the drift backfill (if any) will be directly connected to shaft-seal material when final consolidation has been achieved.

SHAFT-SEAL SYSTEM

Seal components are divided into two categories according to their function and time scale. Temporary seal components, to be constructed of concrete bulkheads and materials containing bentonite, will protect the integrity of the seal system during consolidation. These materials must protect the seal system from intrusion of Rustler Formation brines from above and repository gas from below. Long-term seal components are constructed from blocks of reconsolidated, crushed salt and crushed-salt-based grouts. Crushed salt will consolidate in response to creep closure of the host rock. Grout is used to seal interbeds. These seal components are the primary barrier to radionuclide migration. Candidate seal materials are WIPP crushed salt, bentonite and bentonite-salt mixtures, concrete, and crushed-salt-based grout. Laboratory and modeling studies are being conducted to evaluate these materials.

The four shafts (Figure V-22) will have multi-component seals extending from the drift upward to the surface. Each shaft-seal system (Figure V-26) will consist of an upper seal and a lower seal.

The upper seal is designed to limit seepage of Rustler Formation brine into the lower system so that interstitial brine will not interfere with consolidation of the lower seal. Consolidation should occur at a rate similar to that of the storage panels, proceeding from the drifts upward. Crushed salt will be placed in the upper seal system, but consolidation will be slower, so that these seals are not considered a primary barrier to



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3 Figure V-26. Schematic Design of a WIPP Lower Shaft Seal System (Lappin et al., 1989).

radionuclide transport. The upper seal has only a temporary function, and the concrete is expected to degrade to a hydraulic state similar to silty sand (Stormont and Arguello, 1988).

Lower seals contain crushed salt that will consolidate to nearly 0.95 intact-salt density (Nowak and Stormont, 1987) as the host rock creeps laterally into the shaft. Integrity of the lower seal is maintained by concrete bulkheads emplaced at the bottom of the shaft and at the bottom of the upper seal. Additional bulkheads will be placed in the drifts adjacent to the shafts to protect the lower seals from possible degradation by waste-generated gases. Once these lower seals consolidate, they will form a barrier (in the absence of intrusion) to brine migration and radionuclide transport upward from the repository.

Seal-Material Consolidation Modeling

These studies use the same set of constitutive and structural-analysis models that are used for modeling backfill-mix consolidation and closure for the room, panel seals, and drifts. Consolidation will be most rapid near the bottom of the shaft. Estimates of closure rates that include effects of possible back pressure because of brine and gas within the shaft are important to ensure that temporary seal components provide sufficient protection.

Brine-Inflow and Gas-Outflow Modeling

Brine inflow and gas outflow are important for assessing shaft-seal performance during consolidation, because brine and gas may create a backpressure that retards closure. Predicting the extent to which shaft seals will consolidate requires coupling saturation and creep-closure models. Models must also include brine seepage from above. Bentonite is a seal material only for temporary components, so its structural response (i.e., swelling) is not important for long-term seal behavior. The same models applied to the panel seals can be used for process studies to evaluate different materials and designs.

Disturbed Rock Zone Modeling

Modeling two-phase flow through the DRZ is important for assessing the effectiveness of shaft seals. Flow and transport through fractures of the DRZ could possibly circumvent seal materials. Rustler brines conceivably could leak through the DRZ and saturate the lower seal system. To ensure the integrity of the lower seal system, sensitivity studies of the upper seal system will be performed to evaluate performance. These studies include the DRZ. The programs used for similar studies of panel seals and panels (rooms) can be used for shaft seals.

Flow and Transport Modeling

The undisturbed-scenario analysis requires simulating flow and transport through the repository/shaft system to overlying water-bearing units (e.g., the Culebra Dolomite Member). For human-intrusion scenarios, the primary concern is transport through a plugged borehole and not through consolidated drifts and shafts. Transport through, along, and around shaft-seal materials must be modeled for the undisturbed scenario to determine repository conditions, especially for transient brine and gas flow and closure effects. To handle all scenarios, equations including retardation and fractures for radionuclide transport along the three transport pathways must be solved. Because network models solve only one-dimensional equations along preassigned pathways for fixed fluid fields, more detailed, multi-dimensional modeling may be required to justify the use of these simplified network models in the uncertainty analyses.

Shaft-Seal System

The interface with the next CAMCON module is lateral fluxes of radionuclides into water-bearing units that overlie the Salado Formation. A network model would require benchmarking against more complete and verified dynamical models on idealized test problems designed for WIPP facility geometry. A network model can be formulated to include flow through seal materials, along the seal/host-rock interface, and through the DRZ. In the absence of data, however, calculations are not reliable. The importance of these seals in the overall system must be evaluated by sensitivity analysis to determine if increased understanding of flow and transport is required. Preliminary calculations indicate that radionuclides do not migrate beyond the base of the shaft in the undisturbed-performance scenario (Lappin et al., 1989). Shaft seals are not important in human-intrusion scenarios because boreholes provide a more direct pathway to the accessible environment.

Release Mechanism

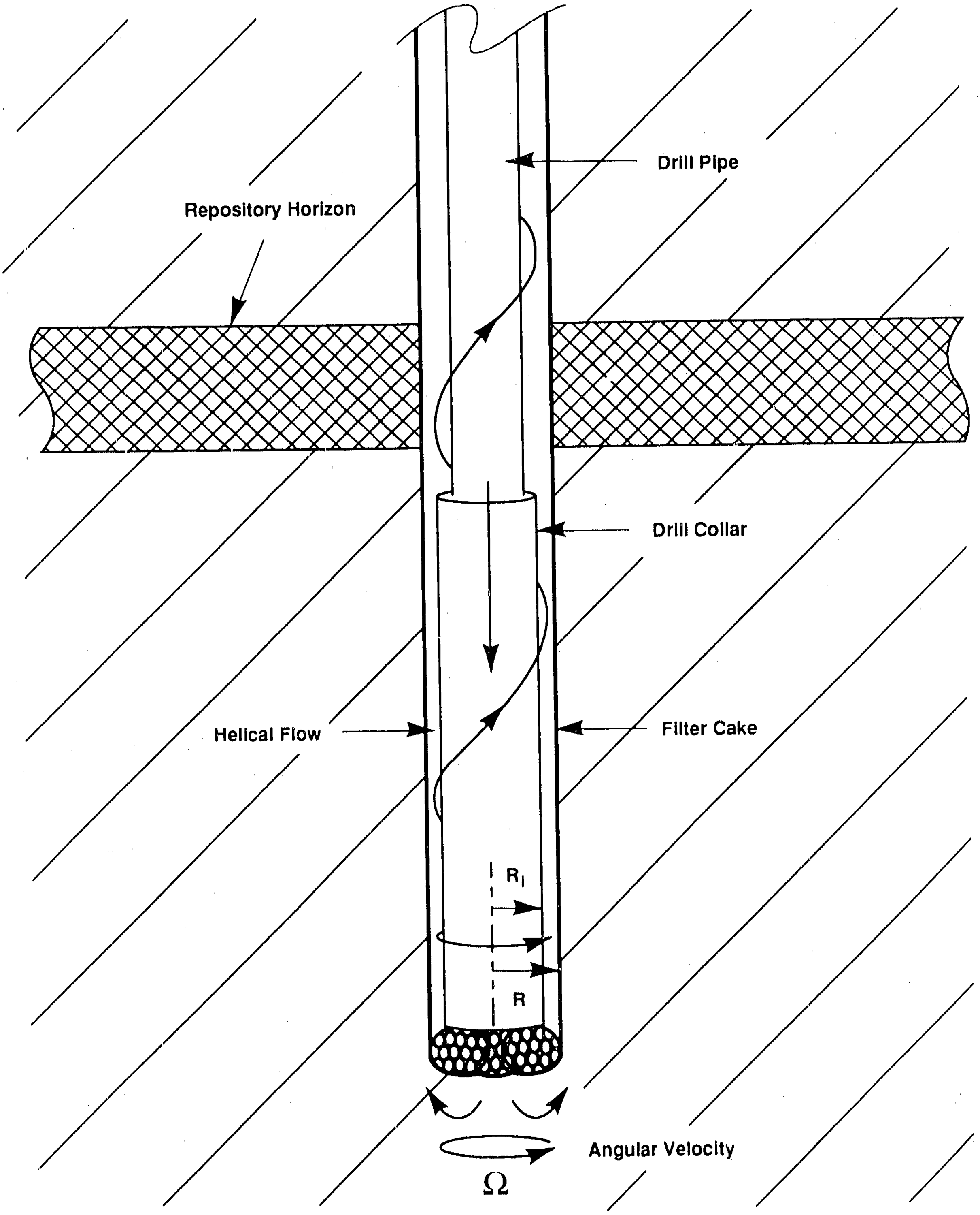
Future exploration for natural resources could result in the repository being breached by a borehole. Radionuclide releases following borehole intrusion will depend on the time of intrusion, conditions within the repository, geology of overlying and underlying formations, and the properties of the borehole. Future drilling technologies are assumed to be comparable to those of the present. Current performance assessments consider two intrusion scenarios: E2, in which a borehole penetrates no features of consequence below the repository, and E1, in which a borehole intersects a pressurized brine reservoir in the Castile Formation below the repository (see Chapter IV). Consequences of deeper penetrations, discussed briefly here, are not believed to be significant.

INTRUSION THROUGH WASTE PANELS

During the drilling operation, some waste material will be brought directly to the ground surface as particulates suspended in the circulating drilling fluid. Some of this material will be cuttings, the material removed by the drill bit from a cylindrical space with a radius equal to that of the bit. As the borehole is extended below the repository, additional material, referred to as "cavings" in drilling terminology, will be eroded from the walls of the borehole at the repository horizon by the circulating fluid. Both cuttings and cavings will be released to the accessible environment in a settling pit at the surface.

The amount of waste removed as cuttings is a simple function of bit diameter. Estimating the amount of waste removed as cavings requires a more complex conceptual model, based on standard drilling technology (Figure V-27) (Berglund and Marietta, in prep.). Drilling fluid, commonly referred to as mud, is pumped down the interior of the hollow drill pipe and out through the drill bit, where it cools the bit and removes cuttings. Fluid returns to the ground surface outside the drill pipe, in the annular space between the pipe (or collar, which is the lowest, and thickest, segment of pipe that supports the bit) and the borehole wall. During the return flow, fluid infiltrates into porous portions of the borehole wall and deposits a layer of muddy filter cake. In moderately porous units, filter cake typically accumulates until the unit is sealed and fluid loss is halted. Sealing of extremely porous units may require adding sealants to the drilling fluid or installing casing.

Because the drillstring (pipe, collar, and bit) rotates, fluid flow within the hole is helical (Figure V-27) (Berglund and Marietta, in prep.). Variables controlling erosion by flowing fluid include the angular velocity of the drillstring, the fluid circulation rate, radii of the components of the drillstring, fluid viscosity, fluid density, borehole roughness, and the critical bulk shear strength of the material being eroded. Parameter values describing variables related to the drilling operation are determined by examining current technology. Driller's logs routinely report velocity (revolutions per minute), circulation (gallons per minute), and drillstring radii. Drilling mud exhibits non-Newtonian behavior, and viscosity must be described with two parameters. Critical bulk shear strength of the waste



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3 Figure V-27. Conceptual Model of Borehole Intrusion. Not to scale. (Berglund and Marietta, in prep.).

will depend on several factors, including the form in which the waste is emplaced and the degree to which the waste has been consolidated by salt creep. Reference waste is a composite material, and values for effective critical bulk shear strength must be determined experimentally.

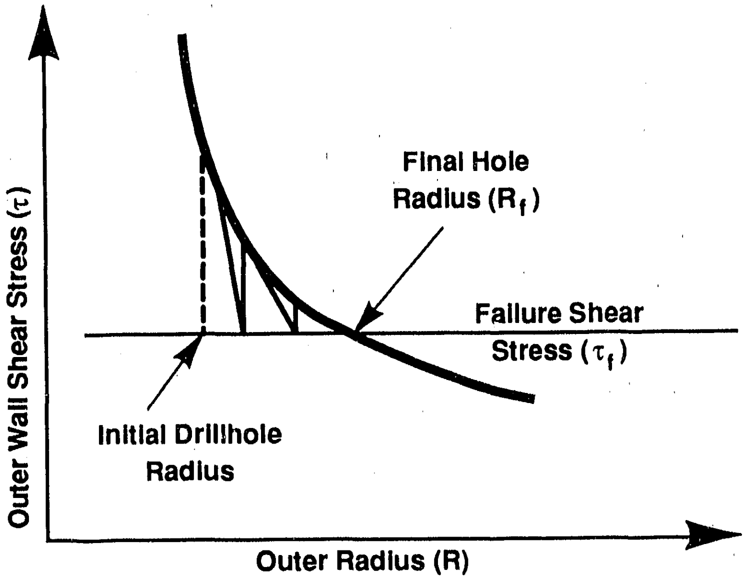
Erosion and transport of waste will occur when the fluid shear stress at the borehole wall exceeds the critical bulk shear strength of the waste (Berglund and Marietta, in prep.). For any given set of conditions, the fluid shear stress at the borehole wall will be a function of annular thickness: as erosion increases hole radius, shear stress will decrease (Figure V-28a). Erosion will cease when shear stress at the borehole wall falls below a failure-shear-stress value corresponding to the critical bulk shear strength of the waste. The total amount of waste removed, including both cuttings and eroded material, will be equal to the volume of a cylinder with a height equal to the repository thickness and a radius equal to the radius of failure by erosion (Figure V-28b).

Erosion is currently simulated by a helical, laminar or turbulent, axial-flow model with fixed values for critical bulk shear strength for the waste corresponding to hypothetical properties of reference-design and modified waste. Radius of the bit is selected by sampling probabilistically over a range based on present drilling practice; simulations in progress will test model sensitivity to variations in all other parameters.

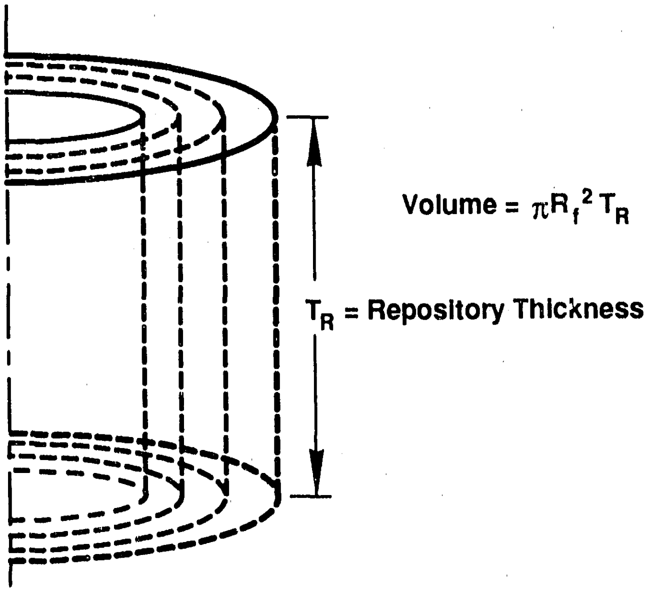
INTRUSION THROUGH CASTILE FORMATION

Pressurized brine has been found in fractured anhydrite within the upper Castile Formation at ERDA-6 and WIPP-12 as well as some thirteen other exploratory wells in the vicinity (Lappin et al., 1989). Hydraulic testing at WIPP-12 indicates that the brine reservoirs is characterized by fracture flow and a limited bulk volume (Popielak et al., 1983). Geochemical studies indicate the WIPP-12 and ERDA-6 brine reservoirs are isolated (Lambert and Carter, 1984). The WIPP-12 reservoir is at a depth of 914 m (3000 ft), about 250 m (820 ft) below the repository horizon. The only possible connection to the repository is through an intrusion borehole (E1).

Early geophysical surveys mapped a zone of structural deformation that could lead to fracturing or development of secondary porosity within the Castile Formation; this zone could possibly contain isolated and stagnant pressurized brine (Borns et al., 1983). Later electromagnetic surveys indicated that the brine could underlie part of the waste panels (Earth Technology Corporation, 1987). WIPP-12 data are used to develop a conceptual model of the brine reservoir for analyzing scenarios that include E1.



a. Relationship between Radius and Shear Stress.



b. Volume of Material Removed.

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Figure V-28. Borehole Erosion as a Function of Shear Stress. (Berglund and Marietta, in prep.).

WIPP-12 penetrated pressurized brine in November, 1981, and produced brine at the surface during flow tests. During this period three flow tests were performed. The last two tests provided flow-rate and pressure histories that can be used to estimate possible flow rates up an intrusion borehole (Lappin et al., 1989). Previous calculations (Lappin et al., 1989; Marietta et al., 1989) ignored the possibility of gas-driven flow, although gas was observed at the WIPP-12 well-head during recovery following the flow tests. Gas coming out of solution during depressurization of the reservoir following an intrusion could enhance flow through the borehole. Two-phase flow is not explicitly included in flow calculations for a Castile pressurized brine reservoir in these calculations. The assigned range of uncertainty in WIPP-12 data is assumed to account for the effect of two-phase flow in the long-term predictions. Response of the Castile brine reservoir to intrusion is characterized by single-phase flow through a network of discrete, discontinuous fractures in heterogeneous anhydrite into a borehole in which both plugs and drilling mud have degraded to sand-like properties.

INTRUSION THROUGH BELL CANYON FORMATION AND DEEPER UNITS

Intrusion will create a potential pathway for fluid migration between the Culebra Dolomite Member, the repository, and the Bell Canyon Formation and deeper units. Relatively little is known about the pressure gradient that would drive flow along this pathway, but data from five wells in the Bell Canyon Formation suggest that flow would be slight, and, in an uncased hole, downward (Lappin et al., 1989).

When the *FEIS* (U.S. DOE, 1980a) was prepared, only data from tests at AEC-8 were available. Freshwater-equivalent heads from the Bell Canyon Formation in that well were higher than Rustler Formation heads, suggesting a potential for upward flow. Mercer (1983) interpreted other well data and concluded, on the basis of potentiometric-surface mapping, that flow at the repository location between the two units would be downward, rather than upward. Based on head data from DOE-2, Beauheim (1986) concluded that flow between units would be upward as long as fluid densities remained constant. In an uncased hole, however, dissolution of halite in the Castile and Salado Formations would increase the density of the rising Bell Canyon fluid, causing flow to stop and reverse direction before reaching the Culebra Dolomite Member. In this interpretation, upward flow can occur only as long as casing remains intact. As casing deteriorates, exposing waste to the borehole fluids, upward flow will cease. Upward flow of fluid from the Bell Canyon Formation is unlikely, therefore, to significantly contribute to radionuclide releases from the repository. Preliminary simulations do not consider consequences of intrusion into units below the Castile Formation.

Human Exposure

Radionuclide concentrations as a function of space and time must be estimated to evaluate compliance with the Individual Protection Requirements (§ 191.15). Undisturbed conditions are simulated for these calculations. Evaluating compliance with § 191.15 requires the analyst to replace the CCDF module in the compliance assessment system with the biotransport and dosimetry modules (Figure III-1). The performance measure becomes annual doses to humans instead of a CCDF. Extra modules must be included in CAMCON to incorporate parameter uncertainty. The simulation produces distribution functions for human exposure. Additional modules are biological-pathways, human-dosimetry, and dose-response modules.

An "exposure pathway" is a potential route through which humans may be exposed to radionuclides or radiation. General pathway categories are external exposure, inhalation, and ingestion. A specific pathway describes the route of exposure within these categories, such as a contaminated-water-to-beef-to-man ingestion pathway. Release points to the biosphere must be considered when defining these biological pathways. Only pathways that arise from withdrawal wells in aquifers with potable water for cattle consumption will be considered for § 191.15; therefore, withdrawal wells are included within the definition of undisturbed conditions. Withdrawal wells will be assumed to provide water for livestock in tanks or ponds, irrigation, and general domestic purposes for local ranches. Livestock ponds will dry after they are abandoned and provide a starting point for airborne releases. Exposure pathways will include:

External pathways due to the rancher's exposure to withdrawal well fluids,

Inhalation pathways due to airborne particulates arising from a dry livestock pond,

Ingestion pathways arising from consumption of food products grown in soil contaminated by airborne particulates from a dry livestock pond,

Ingestion pathways arising from consumption of food products grown with irrigation water from a contaminated withdrawal well, and

Ingestion pathways arising from the consumption of meat and milk products processed from livestock that was watered at ponds or holding tanks contaminated through withdrawal wells.

Many pathways models and dose models exist as well-developed, quality-assured, user-friendly programs (Moore et al., 1979; Till et al., 1987; Napier et al., 1988) and as developmental research programs (Gallegos et al., 1980; Gallegos and Wenzel, 1984; Wenzel and Gallegos, 1985). These models can be applied to the WIPP data base, but all are limited by the completeness of input data.

Input data for dose calculations will be taken from several readily available sources (transfer factors from Baes et al., 1984 and Till and Meyer, 1983; ingestion rates from NCRP, 1984; Till and Meyer, 1983). Committed Effective Dose Equivalents (CEDE) will be taken from U.S. DOE (1988, which has replaced U.S. DOE, 1985), because that document is the primary reference for the DOE and its contractors for calculating dose equivalents resulting from the ingestion or inhalation of radionuclides for the public. Wide variability exists in published parameter values within these references. Calculated 50-year CEDEs can differ by a factor of 10 because of this variability between literature sources (Lappin et al., 1989). No method is available for preferentially selecting transfer factors or ingestion rates from any specific reference, because each reference relied on different health-physics experts for estimating CEDE values. For example, ingestion rates for beef consumption range from 86 g/d (NCRP, 1984) to 206 g/d (Till and Meyer, 1983). If human dose calculations are required, the uncertainty in these input parameters in the literature must be included.

CAMCON: Controller for Compliance Assessment System

The complex disposal system at the WIPP requires that computer programs in the compliance assessment system be controlled by a computerized executive program (Rechard, 1989). CAMCON is the controller for the system (Rechard et al., 1990c). The executive program controls consequence calculations, but is flexible and includes quality assurance (QA). This executive program links distinct model components with little analyst intervention, identifies and traces calculations to insure repeatability and avoid misinterpretation, and controls Monte-Carlo simulations. The controller allows easy examination of intermediate diagnostics and final results. Computer modules within the executive program can be easily replaced for model comparisons. CAMCON modularizes tasks so computer programs for a particular module are interchangeable. CAMCON is fully described in Rechard et al., 1990c.

DATA BASES

Three data bases, primary, secondary, and computational, are included in CAMCON.

Primary Data Base

The primary data base contains measured field and laboratory data gathered during the disposal-system and regional characterization. Because the analysis can be no better than these data, the data base should contain all necessary data for the compliance assessment and repository design, have as little subjective interpretation as possible, and be quality assured. Data base structure must be flexible to accommodate different organizations and unforeseen types of data. Practical experience suggests that a relational data base is best (Rautman, 1988).

Secondary Data Base

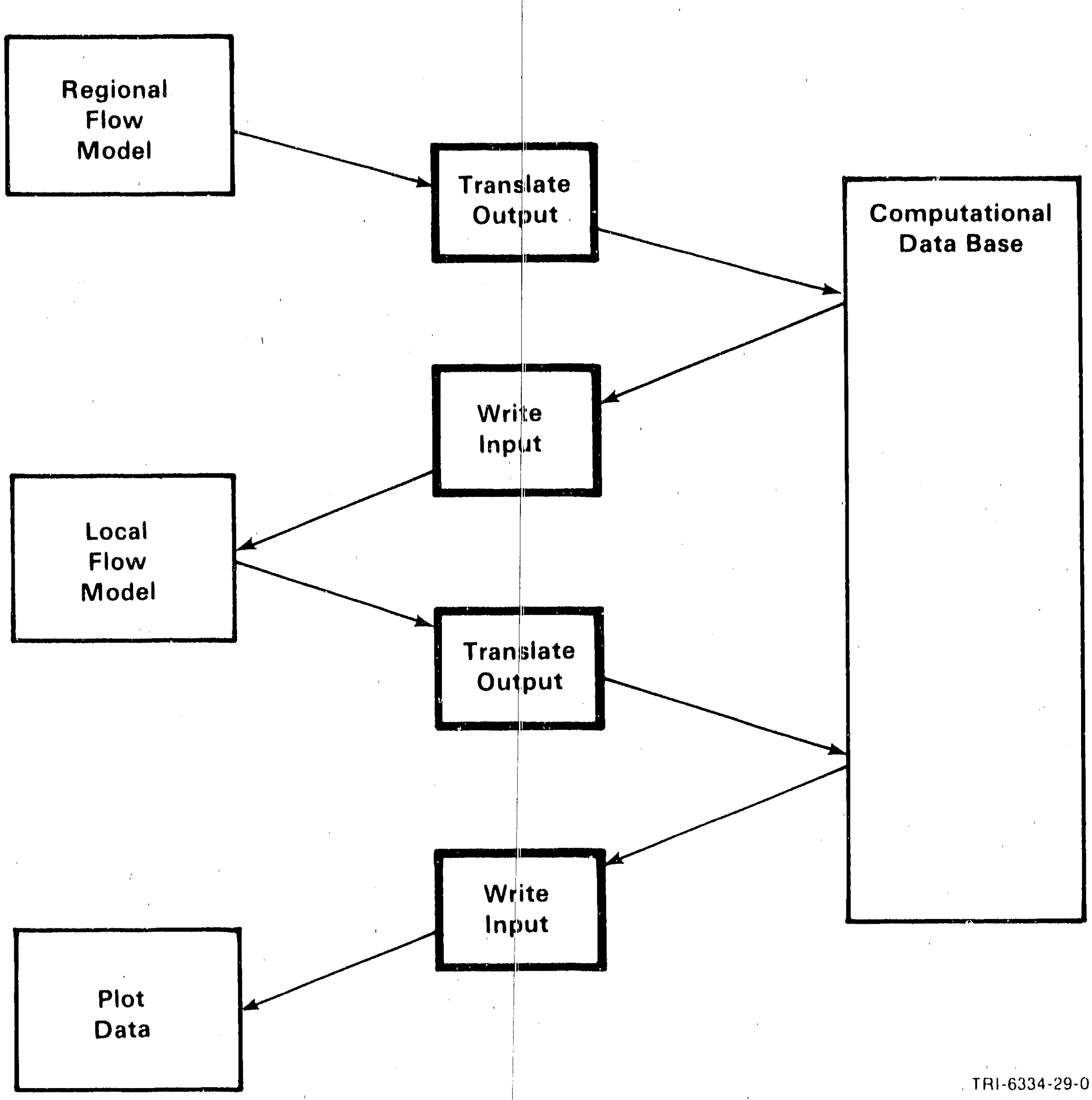
The secondary data base contains interpreted data, usually interpolated onto a regular grid, and incorporates information that comprises the conceptual model of the disposal system. Levels of interpretation can vary from objective interpolation of data combined with subjective judgments to totally subjective extrapolations of data; all interpretations are well documented to ensure the secondary data is reproducible by others. Data from literature or professional judgment are used to fill knowledge gaps to complete the conceptual model. The secondary data base must be accessible to both the analyst and the executive package controlling the system.

Computational Data Base

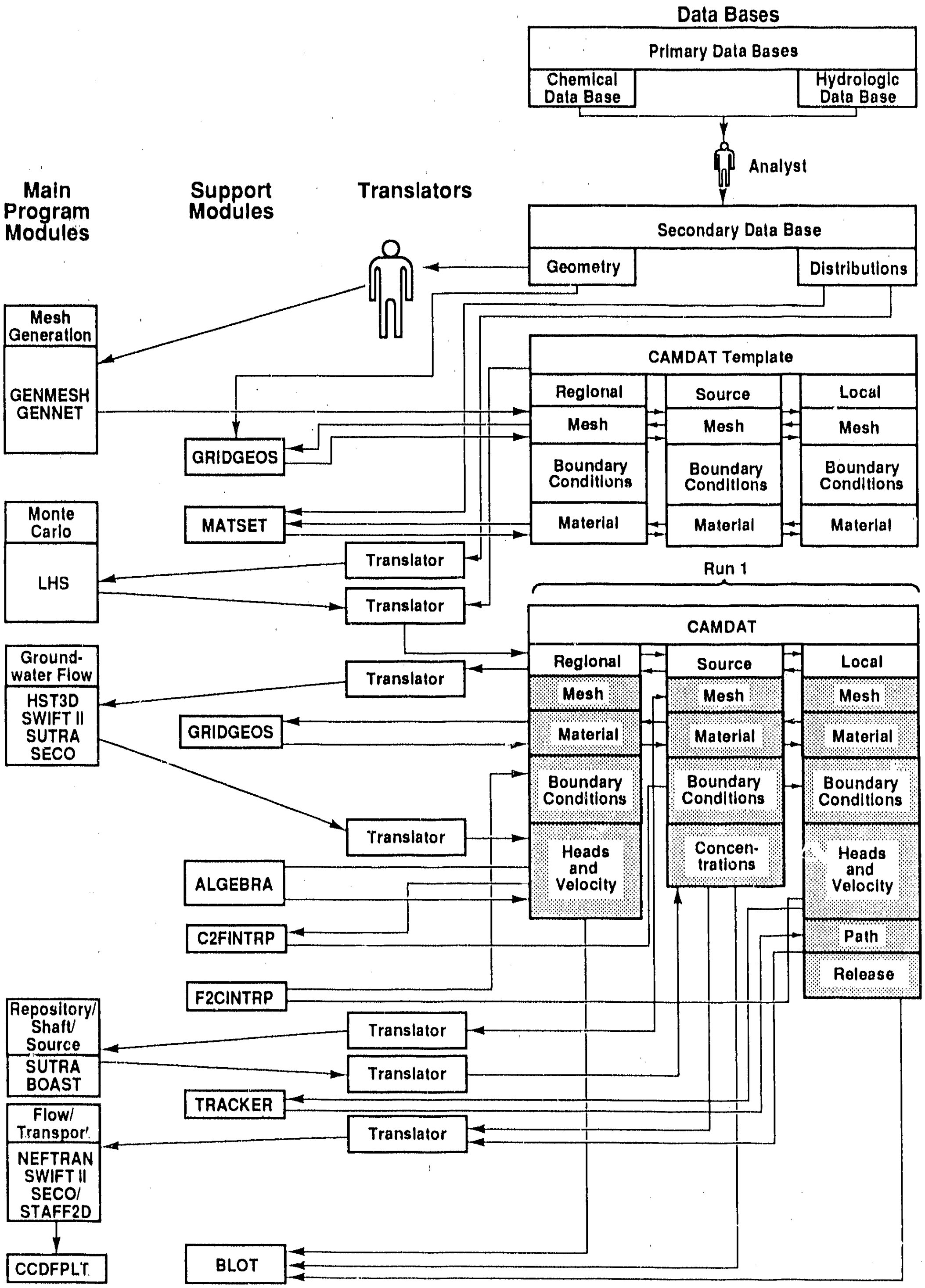
The computational data base is named CAMDAT for Compliance Assessment Methodology DATa. CAMDAT uses a neutral-file format (Figure V-29) so that a series of computer programs can be linked by a "zig-zag" connection rather than the usual serial connection. The file format chosen for CAMDAT was based on GENESIS (Taylor et al., 1987) and EXODUS and their associated data manipulation and plotting programs (Gilkey, 1986a and b, 1988b; Gilkey and Flanagan, 1987). CAMDAT is fully described in Rechard et al., 1990c.

PROGRAM LINKAGE AND MODEL APPLICATIONS

Program linkage and data flow through CAMDAT is controlled by CAMCON. Computer programs that make up the CAMCON system are major program modules, minor program modules, and translators (Figure V-30). Major program modules refer to programs that represent major tasks of the consequence modeling. Minor program modules refer to programs such as interpolators that are necessary to facilitate use of major program modules. Translator program modules refer to programs that translate data either into or out of the computational data base.



3 Figure V-29. Coupling Through a Computational Data Base using a "Neutral File" (Rechard, 1989).



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3 Figure V-30. Algorithm for Logical Data Flow During Compliance Assessment (Rechard, 1989).

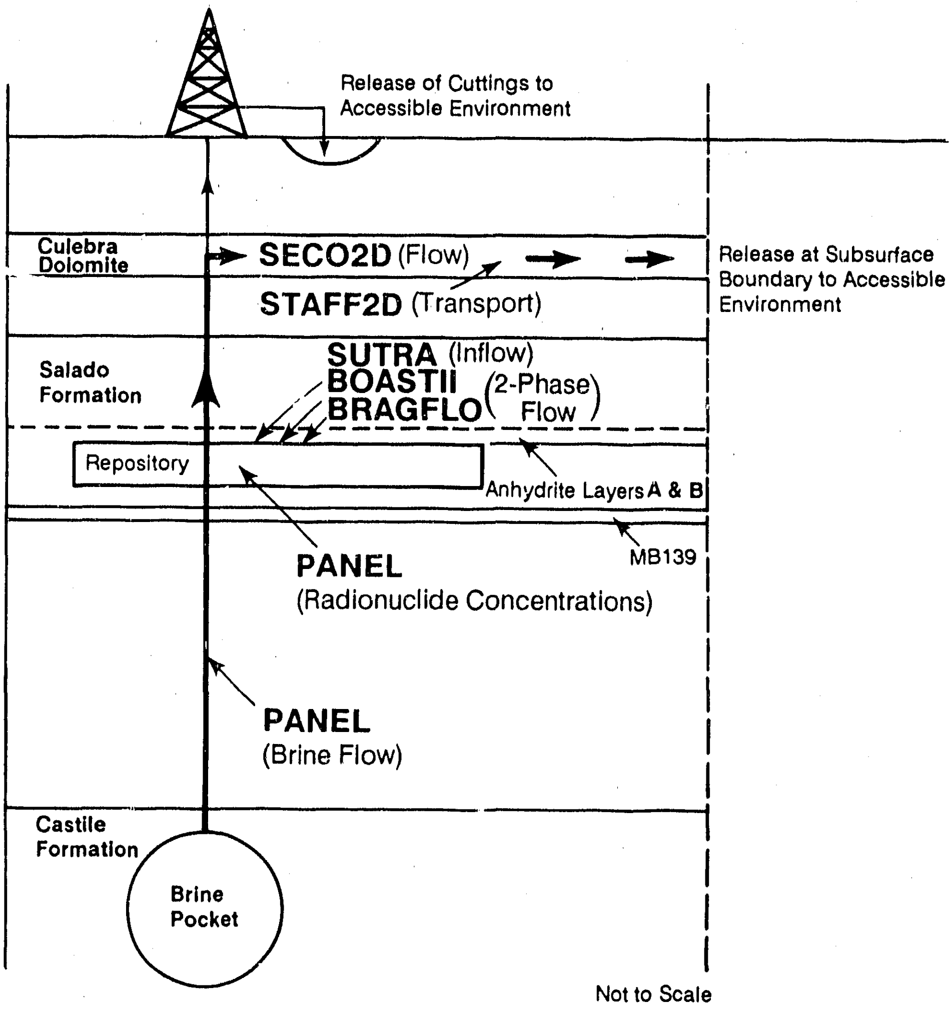
Figure V-31 shows how major programs within CAMCON are used to evaluate human intrusion scenarios. Seven of the major CAMCON programs are discussed below: SUTRA, SECO2D, STAFF2D, BOAST II, BRAGFLO, NEFTRAN, and PANEL.

Saturated-Unsaturated Transport Program (SUTRA)

The SUTRA (Saturated-Unsaturated TRAnsport) program evaluates density-dependent, saturated or unsaturated, groundwater flow in rigid, porous media with either (1) transport of a single-species solute subject to nonlinear equilibrium adsorption and zero- and first-order production or decay or (2) transport of thermal energy in the groundwater and solid matrix of an aquifer. SUTRA employs a two-dimensional hybrid finite-element and integrated-finite-difference method to approximate the governing equations. The primary results are fluid pressures and velocities and either solute concentrations or temperatures as they vary with time (Voss, 1984). SUTRA has been included in CAMCON as an optional module for Monte Carlo simulations (Rechard et al., 1990c).

SUTRA is used in this report for predicting brine flow into an intruded waste panel. Current modeling efforts are concerned with brine flow throughout a radially symmetric, two-dimensional matrix consisting of a waste panel surrounded by the local stratigraphy. The borehole lies along the axis of symmetry. The modeled geologic matrix includes the surrounding intact host rock, the nearby disturbed rock zones, anhydrite layers A and B, and MB139 (Figure V-32). The modeled panel volume includes the salt pillars between rooms. The panel is assumed to be consolidated and compressed by salt creep to a final thickness of two meters. Because the waste panel was modeled to include salt pillars, porosity was adjusted so that the product of the porosity and the total enclosed volume would equal the net pore volume of the enclosed volume. Hence, the porosity used in the calculations is about 0.40 times the estimated waste porosity (Butcher, 1990b). No other waste properties are adjusted.

The backfilled borehole was modeled with appropriate initial properties determined in each Monte Carlo sample. However, the permeability was allowed to change as a function of elapsed calculation time in an attempt to model the closure of the borehole due to creep of the surrounding host rock. SUTRA does not model true mechanical deformation. Thus, to further refine the closure model, the borehole was divided into three concentric tubes whose permeabilities changed in accordance with a bilinear function of closure data. The bilinear function included the effective permeability, the backfill permeability, the host rock permeability, and the normalized radial closure. Based on modeling of salt creep, maximum radial closure was assumed



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3 Figure V-31. Major CAMCON Programs Used in Evaluating Human Intrusion Scenarios.

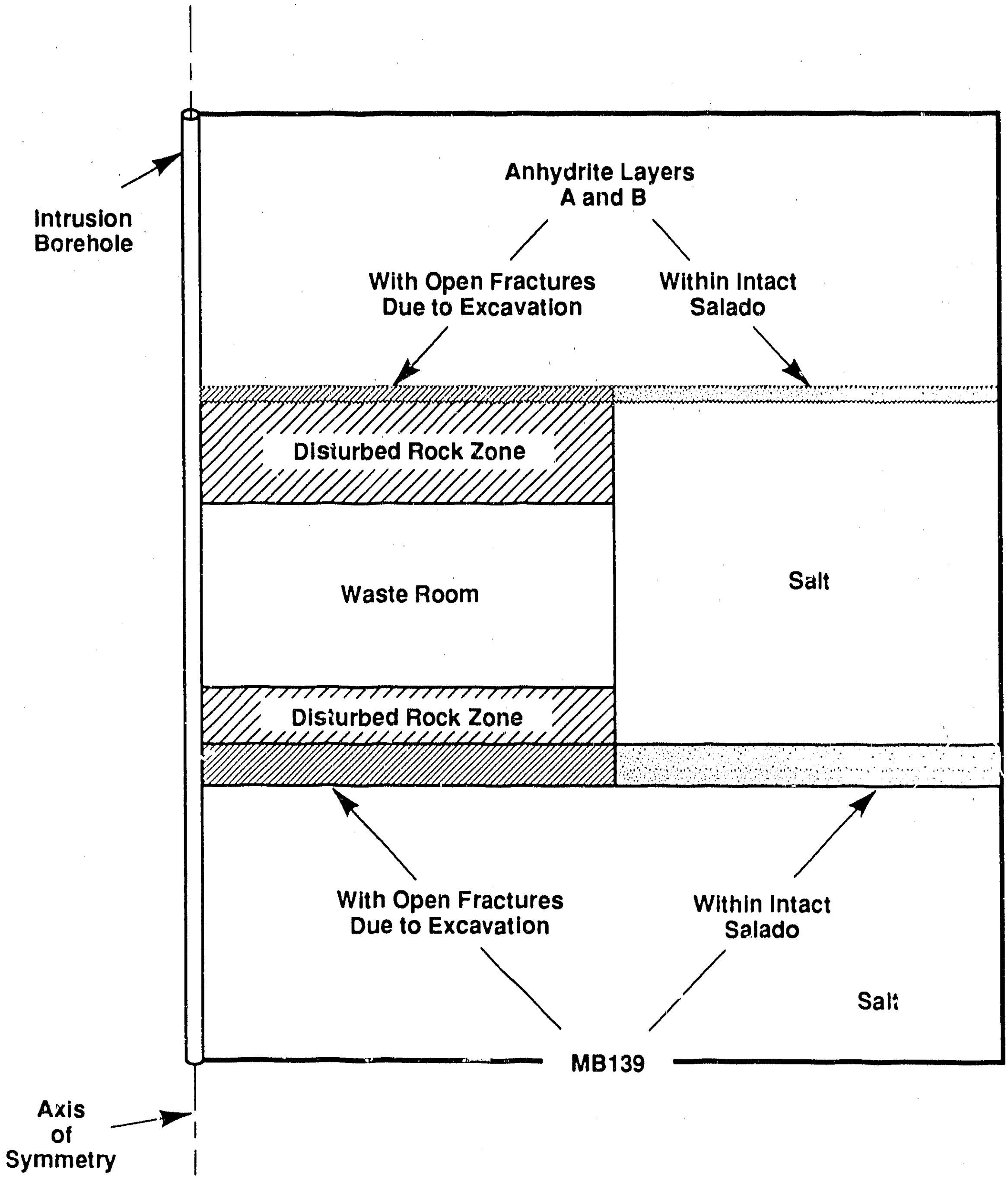

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Figure V-32. SUTRA Geologic/Waste Panel Model.

3

to be 80 percent (Figure V-33) (Sjaardema and Krieg, 1987). No credit was taken for the possibility that irregularities in the stress field near anisotropic interbeds could result in complete closure of boreholes.

For brine flow calculations, four parameters were sampled: the host rock capacitance, the host rock permeabilities (isotropic), the borehole area, and the backfill permeabilities (isotropic). Thus, the time-dependent values of net borehole permeabilities were sampled. No other material properties were sampled. The initial conditions for the transient (post-intrusion) SUTRA calculations were defined by a preceding steady-state calculation for each vector. The steady-state SUTRA calculations produced restart files from which the transient SUTRA calculations were started. Material property description for each steady-state vector (run) is identical to the corresponding transient vector except that no borehole exists in the steady-state model. The boundary conditions in the steady-state model are lithostatic on all boundaries except the axis of symmetry where no-flow conditions are imposed. Gravity is assumed in all calculations. The boundary conditions for the transient model are no-flow on all boundaries except at the top of the borehole in the modeled domain. There the pressure varies linearly from lithostatic to hydrostatic in the first 100 years (to simulate a degrading seal) and then remains constant (hydrostatic).

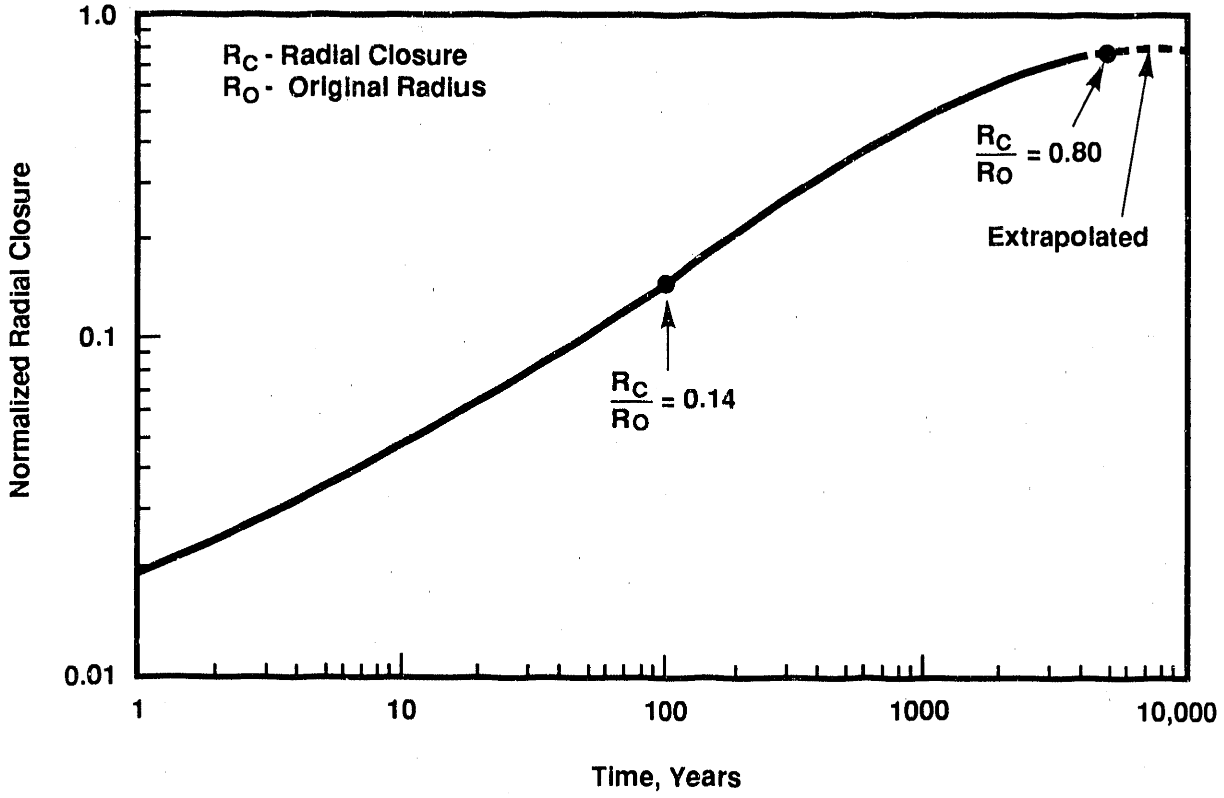
Panel Program (PANEL)

The PANEL program (Rechard et al., 1990c) estimates rates of discharge of brine and radionuclides to the Culebra Dolomite Member of the Rustler Formation following the interconnection by one or more boreholes of a waste panel, the Culebra Dolomite, and possibly a pressurized brine reservoir in the Castile Formation. Discharge rates are estimated using coupled models of geochemical processes in the repository and fluid flow within the repository, the borehole or boreholes, and the Castile Formation.

Geochemical processes modeled include radioactive decay and the dissolution of radionuclides within the waste panel. Required parameters for the geochemical calculations are the initial inventory of all radionuclides, half-lives and decay chains for all radionuclides, solubility limits for all elements, and the pore volume of the panel. Assumptions inherent in the model include chemical equilibrium and uniformly distributed waste within the panel. Sorption of radionuclides within the panel is not considered.

The PANEL model considers four components of fluid flow separately: upward flow of brine from the Castile Formation due to the pressure differential between the brine reservoir and repository; brine flow from the Salado

2



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3 Figure V-33. Logarithmic Normalized Closure Rate for Baseline Shaft (Sjaardema and Krieg, 1987).

Formation into the waste panel; circulation of brine through the waste within the panel; and upward flow within the borehole from the panel to the Culebra Dolomite. Brine inflow from the Salado Formation as a function of time after intrusion is calculated using SUTRA, as described in the previous section. Required parameters for the Castile Formation include the initial brine reservoir pressure and the bulk storage coefficient. Other required parameters include the time of intrusion, the dimensions and locations of boreholes, and hydraulic conductivity within the waste panel and the boreholes. Borehole diameter and hydraulic conductivity may be varied arbitrarily with time to simulate plug degradation and creep closure.

All flow is assumed to occur as a single fluid phase, neglecting possible effects of exsolution of gases from Castile brine and possible precipitation of solids within the borehole. All flow is also assumed to be governed by Darcy's law, and can therefore be completely characterized by data on hydraulic conductivity, specific storativity, pressure gradients, and component geometry. Pressure in the Culebra Dolomite is assumed to remain constant. Transient behavior is controlled only by depletion of the brine reservoir, and all components are assumed to be at steady state with respect to boundary pressures at any given time. Change in brine reservoir pressure is assumed to be proportional to volume of fluid discharged.

Rates of fluid discharge to the Culebra Dolomite are calculated for discrete time steps. Radionuclide discharge at each time step is calculated assuming that fluid entering the waste panel displaces an equal volume of fluid containing the prevailing concentration of all radionuclides. Radionuclide concentrations within the waste panel are recalculated at each time step by updating the waste inventory to account for radioactive decay, mixing the new, uncontaminated brine with the brine remaining in the waste panel from the previous time step, and calculating new equilibrium concentrations of all isotopes.

For single intrusion scenarios, flow through the waste and dissolution of radionuclides occur only as a result of brine inflow from the Salado Formation. The increased borehole pressure gradient resulting from penetration of a Castile Formation brine reservoir is assumed to have no effect on brine inflow, and the dissolution and transport of radionuclides are therefore the same for the E1 and E2 scenarios. This assumption may overestimate brine inflow and radionuclide transport for the E1 scenario. In the case of multiple intrusions, flow through the waste may occur between boreholes, and Castile brine may also dissolve and transport radionuclides.

Sandia Ecodynamics 2 Dimensions Program (SECO2D)

The SECO2D (Sandia Ecodynamics 2 Dimensions) (Roache et al., in prep.) program solves the fundamental equation for hydraulic head and includes the following capabilities:

Regional and local area grid solutions,
General boundary conditions,
Efficient problem definition and output,
Flexible specification of initial conditions,
Options for cell-centered or node-centered grids,
Automated specification of grid spacing (including uniform spacing or power-law stretching for increased resolution near physical features),
Automated specification of time steps (including uniform spacing or power-law stretching for increased time resolution near events),
Parameterized climatic variations,
Artesian or water table conditions,
Flexible specification of initial conditions, boundary conditions, and rivers/lakes,
Particle tracking capability, and
Efficient multigrid (semi-coarsening) solvers.

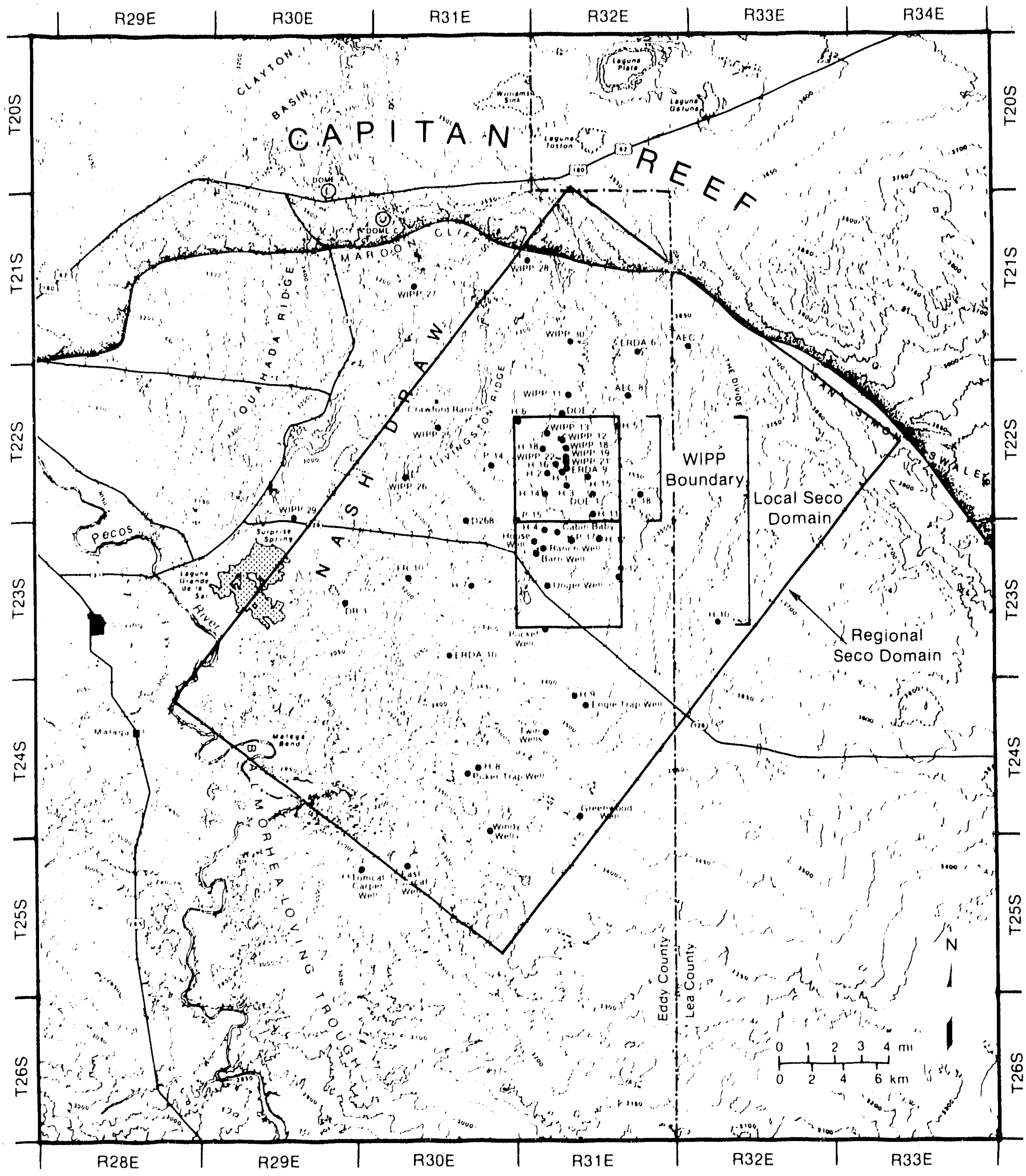
SECO2D has been included in CAMCON as an optional groundwater module to be used in both regional and local domains (Rechard et al., 1990c).

In SECO2D, the aquifer conditions may be either confined (artesian) or unconfined (water table), and the determination is automatic (i.e., internal to SECO2D). Drier regions of the aquifer may naturally recharge. The multigrid solvers, important for high-resolution studies, have nearly optimal operation counts, that is, computational time proportional to the number of nodes. Initial conditions may be specified by using the value set in the aquifer-defining grid, specifying other values by way of a separate routine, and solving the steady-state problem with the specified boundary conditions and all wells turned off (automated). Unlike most computer programs that model groundwater hydrology, SECO2D allows boundary conditions to be specified generally. These can be specified head, specified flux (including non-zero), mixed, and adaptive (flux at inflow, head at outflow). These conditions are specified along any number of independent sections on any boundary, defined independently of the discretization. Sections of specified flux boundaries can simulate recharge boundaries and can be modified by climatic variation.

The particle tracking algorithm in SECO2D is based on a linear interpolation of the Darcy velocities in space (consistent with the second-order spatial accuracy of the flow solution) and an adaptive fifth-order integration in time (Runge-Kutta-Fehlberg). The tracker integrator is higher order in time than the flow solution. This ordering is not inconsistent or unbalanced, because the flow solution involves an Eulerian description whereas the particle solution is inherently Lagrangian. For example, even a steady-state flow solution (with zero time truncation error) and a velocity field linearly varying in space produce a particle path that involves exponential functions, thus justifying the higher-order accuracy in time. A particle trajectory through the local and regional grids is mapped (shifted and rotated) for display in either or both the local and regional grids. Flow and particle tracking were tested on model problems and exhibit the expected accuracy.

Regional and local domains for SECO2D used in this report are shown in Figure V-34. The regional domain is based on natural boundaries and offers coarse resolution through stretched, irregular rectangular gridding. The local domain in current analyses has fine resolution with uniform rectangular gridding. Regional and local grids are illustrated in Figure V-35. Computational efficiency is derived from using fewer grid points. While currently not completely tuned, the model will be refined during the next year to achieve the necessary efficiency. Climate variability and boundary condition uncertainties are entered along regional boundaries. Heads and fluxes for recharge are changed along the north and west boundaries. Heads are also changed along the south and west boundaries. Boundary condition uncertainties are sampled along the east and south boundaries. Heads and fluxes at the boundaries are assumed to be directly proportional to external change in precipitation (see Figure V-18). In the interior of the computational domain—both regional and local—leakage can include the effects of subsidence. Leakage could also include similar effects of any process that results in an internal vertical connection (for example, breccia pipes, abandoned boreholes, sink holes, etc.). However, these latter effects are not currently included in the conceptual model.

Preliminary sensitivity studies indicate that climate variability has no significant effect on flow and transport to the south from WIPP over a 10,000 year time scale (Marietta et al., in prep.). Increased vertical connection due to subsidence from potash mining is also assessed as having little effect. These factors therefore, were not explicitly included in the present assessments, although these parameters were included in the sampling. Further sensitivity analyses using different regional and local recharge assumptions are required to finalize these submodels for final consequence analysis.



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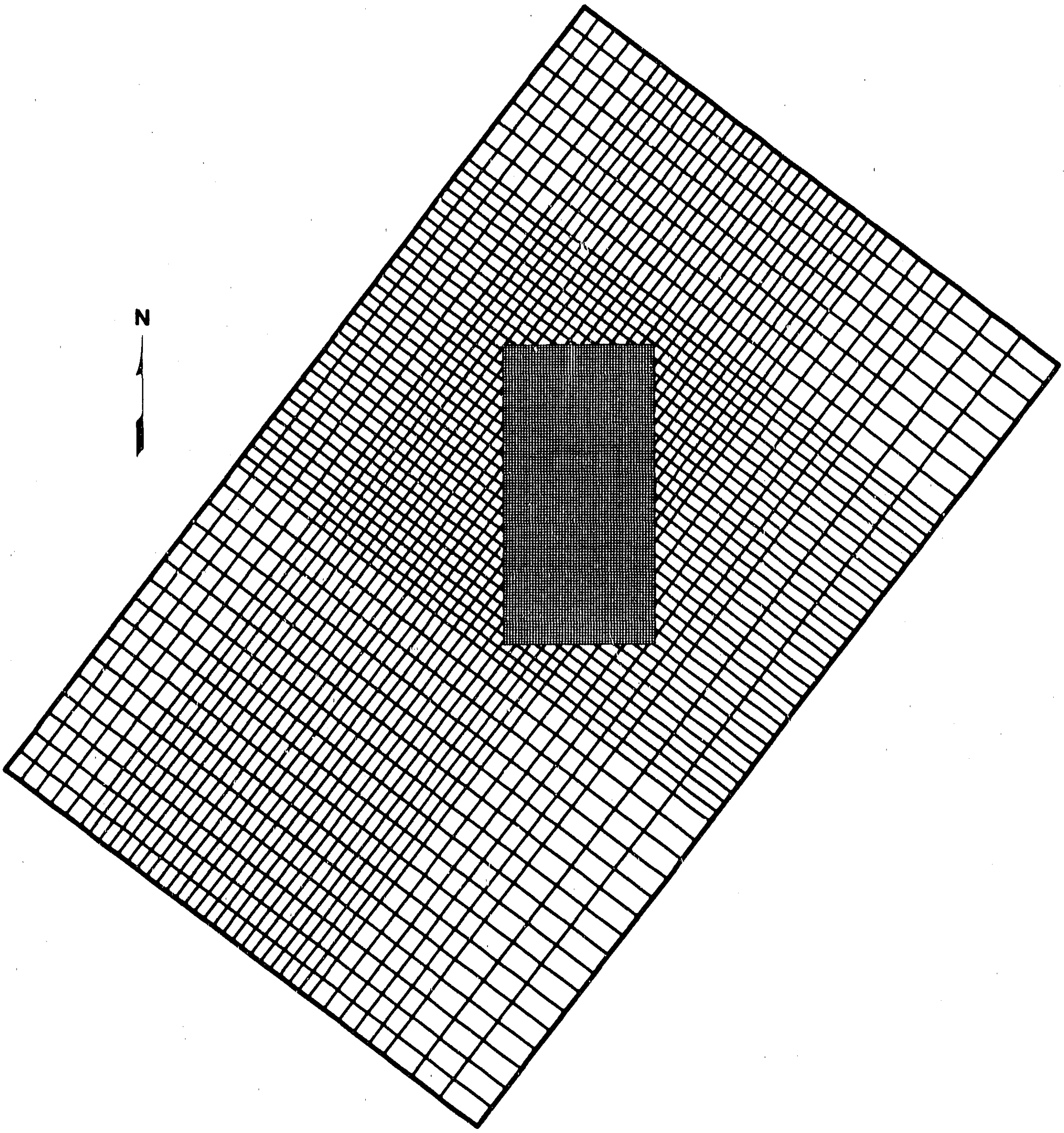
3 Figure V-34. SECO2D Model Regional and Local Domains.



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3 Figure V-35. Regional and Local SECO2D Domain Grids.

Solute Transport and Fracture Flow in 2 Dimensions Program (STAFF2D)

STAFF2D (Solute Transport and Fracture Flow in 2 Dimensions) is a two-dimensional finite element program designed to simulate groundwater and solute transport in fractured or granular aquifers (Huyakorn et al., 1989). The original version was developed under a joint cooperation project between HydroGeoLogic, Inc. and the International Ground Water Modeling Center of Holcomb Research Institute. Sandia National Laboratories improved STAFF2D by adding a five-multiple-chain-length capability and incorporating the AMG (Algebraic MultiGrid) algorithm; the module can now treat fractured aquifers that are either confined or unconfined. Fractured porous media are represented using both discrete-fracture and dual-porosity approaches. The flow and transport equations are solved using improved, finite-element algorithms with special features designed to handle aquifer-aquitard systems and options to account for water-table boundary conditions and fracture-skin effects.

The AMG algorithm achieves high efficiency that is remarkably independent of grid size. The algorithm iterates the discretized equations on the specified (finest) grid, and on a sequence of subgrids. In simple iterative methods, the long-wavelength errors decay slowly, delaying iterative convergence. In multigrid, these errors are transferred to coarser grids where they have "short" (with respect to grid increments) wave-lengths and therefore decay more rapidly. The subtle part of the algorithm is the transfer of information between grids. AMG algorithms generalize this multigrid concept. Whereas classical multigrid methods connect the hierarchy of resolutions (i.e., the multiple grids) by constructing ordered subgrids, the AMG algorithms do so by directly examining the relative strengths of the connections between unknowns in the array elements, that is, algebraically, rather than geometrically. Like classical multigrid methods, the advantage of AMG (over simple iterative or direct methods used in traditional groundwater flow programs) is more pronounced for finer resolutions. Incorporating an AMG solver has produced a factor of 5 to 10 improvement in execution speed for reasonably sized grids in STAFF2D.

STAFF2D takes into account (a) fluid interactions between the fractures and porous matrix blocks; (b) advective-dispersive transport in the fractures and diffusion in the porous matrix blocks and fracture skin; and (c) chain reactions of radionuclide components. Major advantages of STAFF2D are (a) capability to model the fractured system using either the dual-porosity or the discrete-fracture modeling approach or a combination of both; and (b) capability to simulate both flow and transport. STAFF2D has been added to CAMCON as an optional radionuclide transport module to be used with or without a separate groundwater-flow module (Rechard et al., 1990c).

The STAFF2D domain for this report is shown in Figure V-36. STAFF2D is used only in a transport domain that is smaller than the flow domain because STAFF2D has a slow execution time. The local transient flow field from SECO2D is fed into STAFF2D, and STAFF2D only does transport simulation. Options in radionuclide retardation submodels used in this report are (1) discrete fractures with clay linings, and (2) dual porosity.

Black Oil Applied Simulation Tool (BOAST II)

The BOAST II (Black Oil Applied Simulation Tool, enhanced version) program, a petroleum reservoir model, simulates isothermal Darcy flow in three dimensions. BOAST II assumes that reservoir fluids can be described by three fluid phases (oil, gas, and water) of constant composition with physical properties that depend only on pressure. BOAST II uses a finite-difference, implicit pressure, explicit saturation (IMPES) numerical technique for solving the three differential equations that describe the simultaneous flow of the three phases. In the compliance assessment system, BOAST II simulates flow of brine and gas and the effects of gases generated by the waste so only two phases are used. Both direct and iterative techniques are available to solve the resulting system of algebraic equations. Except for flow boundaries, boundary conditions must be specified by wells. The well model in BOAST II allows rate or pressure constraints on well performance to be specified, so that gas generation and brine sinks can be simulated in a variety of realistic ways. Output from the model includes time-dependent pressures and saturations of each phase in each grid block of the model region (Fanchi et al., 1987). BOAST II has been included in CAMCON as an optional module for two-phase flow within waste panels and nearby Salado Formation, including interbeds.

Current modeling for transport is concerned with gas and brine flow in a waste panel with an intrusive borehole. Model geometry is the same as that used for SUTRA (Figure V-32); the borehole lies along the axis of symmetry, and the geologic matrix about the waste panel includes the disturbed rock zone about the waste panel, anhydrite layers A and B and MB139 (both within the intact Salado Formation and with fractures opened during excavation), and the surrounding host rock. The gas source in the waste panel in this preliminary assessment corresponds to the maximum hydrogen gas generation rate (Brush and Lappin, 1990). Gas generation is sampled over the intrusion time frame. When intrusion occurs, the pressure drops to hydrostatic. BOAST II calculates transient responses both before and after intrusion for two-phase Darcy gas and brine flow. Flow through the waste panel is recorded for input to the ROOM model to calculate radionuclide fluxes into the borehole.

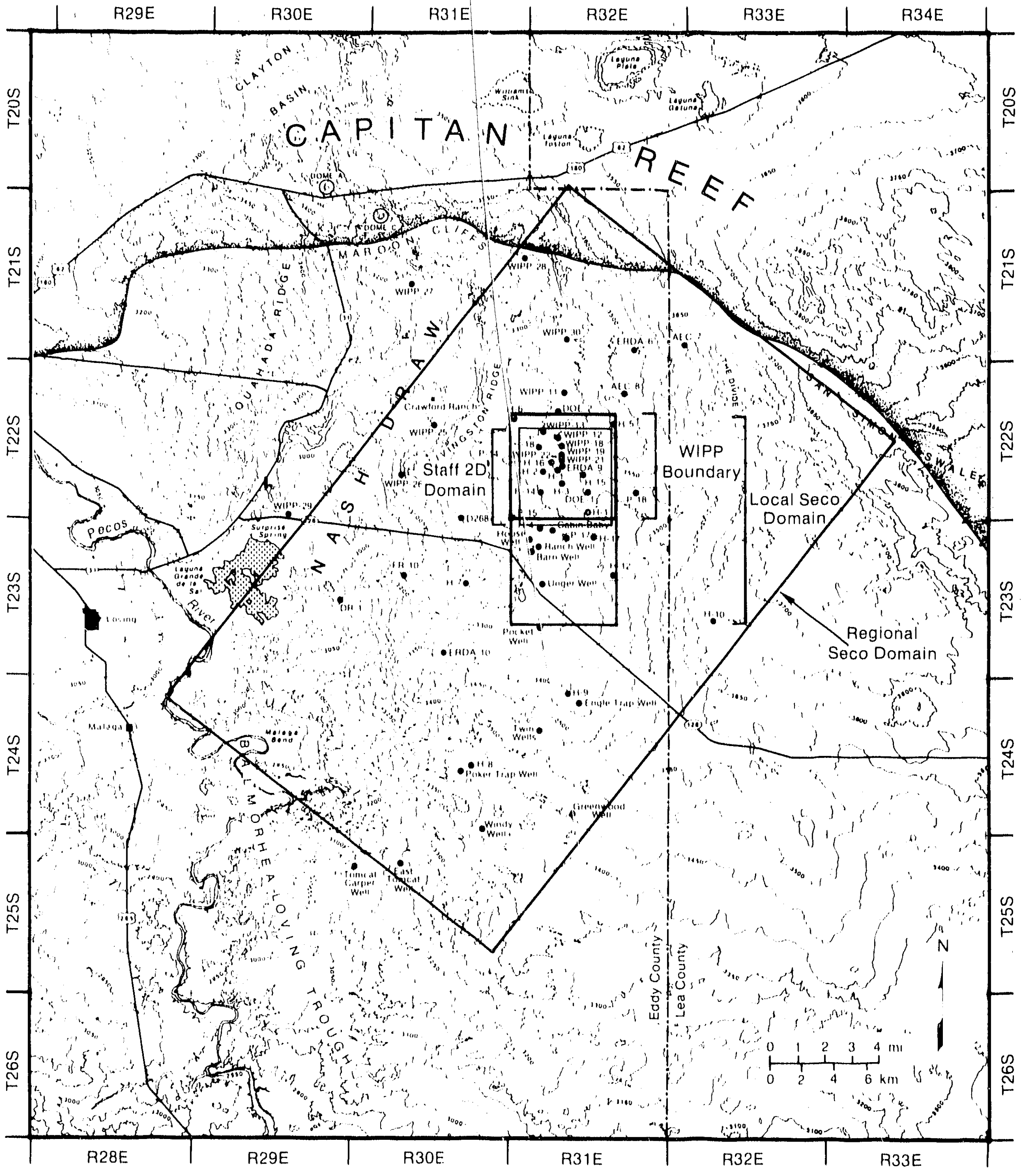

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Figure V-36. STAFF2D Domain.

A typical pressure history in the waste region shows a rise above lithostatic pressure. BOAST simulates the flow of gas and brine into the interbeds and halite before intrusion. On intrusion, BOAST simulates the transient response of brine flow into the intrusive borehole through interbeds and halite, and through the waste panel as gas continues to be generated (depending on intrusion time).

Transient Two-Phase Flow Program (BRAGFLO)

BRAGFLO is a recently modified version of TSRS (Tar Sand Reservoir Simulator) (Vaughn, 1986) for simulating transient two-phase flow of brine and gas in a porous reservoir. BRAGFLO uses finite-difference techniques to discretize the fundamental partial differential equations that describe mass conservation of each phase.

BRAGFLO is a fully implicit model and therefore does not suffer from the numerical instabilities and excessively small time step requirements of explicit or IMPES models such as BOAST II. The discretized partial differential equations are solved using Newton-Raphson iteration with an automatic time step algorithm.

A more detailed discussion of the use of BRAGFLO in this preliminary performance assessment is contained in Chapter VI.

Network Flow and Transport Program (NEFTRAN)

The NEFTRAN (NEtwork Flow and TRANsport) program simulates radionuclide transport through porous or fractured media. The model assumes that all significant flow and radionuclide transport take place along discrete one-dimensional legs or paths. These legs are assembled to form a multidimensional network representing the flow field. Using specified pressure boundary conditions, NEFTRAN solves the flow equations. The source term within NEFTRAN contains both leach-limited and solubility-limited models and can also account for dilution of contaminants with a mixing-cell model. Each leg in the radionuclide migration path serves as a source to the next leg, and the user has the option of selecting each leg as either porous (single porosity) or fractured (dual porosity). A distributed velocity method calculates travel times of each radionuclide in each leg of the path. An important feature of NEFTRAN is that it allows transport of multiple radionuclide chains in a single run. The results include the rate of discharge and concentration of each radionuclide in each chain at the end of the migration path as a function of time. In addition, integrated discharges and concentrations over the problem time, peak concentration, and concentration at a specified time can be obtained. Because of the speed of the computations, repeated trials from Monte Carlo sampling are possible, which allow parameter sensitivity to be examined (Longsine et al., 1987).

NEFTRAN has been added to CAMCON as an optional module for larger system sensitivity and consequence analysis (Rechard et al., 1990c). NEFTRAN was previously used in both undisturbed and human intrusion scenario analysis (Marietta et al., 1989). In this report, NEFTRAN was replaced with a linked system of the above programs for the human intrusion analysis.

Status of Compliance Assessment System

Performance assessment for the WIPP is a dynamic process (see "Performance Assessment Process" in Chapter III), and the compliance assessment system undergoes continuous refining and updating. A discussion of the late-1990 status of the compliance assessment system for the natural barrier and repository/shaft systems and CAMCON follows.

NATURAL BARRIER AND REPOSITORY/SHAFT SYSTEMS

As indicated in Chapter III, the performance assessment must build from components to subsystems and finally to the total system. The computational bases currently being developed for the natural barrier systems and the repository and shaft systems are summarized here to examine the status of the compliance assessment system. Much of the disposal-system characterization work that has already been completed has been omitted to focus on work in progress. When complete, the compliance assessment system will include a performance assessment mathematical model derived from the conceptual model, a computer program or program segment, and data sets corresponding to each important component or subsystem affecting the total-system performance. The completeness of these computational bases can be qualified as "preliminary," "intermediate," or "advanced." The status of the bases for the system are shown in Table V-7 (placed at the end of this discussion).

"Preliminary," when applied to the conceptual model uncertainty, means that understanding of the component or subsystem is intuitive and incomplete; when applied to the compliance assessment system, "preliminary" means one or more areas of research, modeling, or computer programming is only planned or recently initiated. This qualifier also indicates sensitivity analyses have not yet determined the overall importance of the component or subsystem to the total system. "Intermediate," when applied to the conceptual model, means that the important processes are identified and understood. When applied to the compliance assessment system, "intermediate" means that some site specific data are available, or models and computer programs are being developed, or both, and importance of the component or subsystem to performance assessment or adequacy of the data are not fully known. "Advanced" means uncertainty in the conceptual models for the component or subsystem is adequately understood, or the data base is adequate for performance assessments, or the models and computer programs are ready, depending on which of the computational bases the qualifier is applied to.

The status of each component or subsystem listed in Table V-7 should be interpreted separately. For example, understanding of the conceptual model uncertainty for wall closure of the individual rooms is advanced. The performance-assessment computer programs for the closure and compaction module are partially complete, while benchmarking of these computer programs against the design system is just beginning. The performance-assessment data base for this module is partially complete.

The list of component conceptual models in Table V-7 reflects the compliance assessment system in late 1990. The status of the compliance assessment system will change as the WIPP research and performance assessment programs advance. Some changes will reflect ongoing research and the availability of new data or models. All changes will reflect performance assessment analyses that show whether an acceptable level of information has been achieved for each component and sybsystem. Thus, if sensitivity analyses indicate a component or subsystem has little impact on total-system performance, relatively large uncertainties in the model or an incomplete data base could be acceptable and the status of the model deemed "advanced". Alternatively, for those components or subsystems where system sensitivity is high, detailed models and extensive data bases may still result in an intermediate classification.

CAMCON SYSTEM

Table V-8 shows the status of the 49 composite programs now in CAMCON. As the table indicates, program status is shown as "done," "working," and "under development." "Done" means that the program is complete and no further modifications are anticipated; "working" indicates that the program does produce results, but the improvements indicated in the table are planned; programs with the "under development" indication do not produce results at this time. Specific information on seven major CAMCON programs is provided in the section "Code and Model Applications." Several important programs have not been included in CAMCON yet because the research is preliminary or because of time constraints. Those programs will also require pre- and post-translators.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1]

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
(A) RADIONUCLIDE TRANSPORT IN NON-SALADO STRATA				
GEOSTATISTICS				
Culebra Transmissivity Distribution				
High Transmissivity Zone Definition	Intermediate			
Uncertainty in High Trans Zone	Intermediate			
Compliance Assessment Module		Intermediate	Preliminary	Intermediate
2-D GROUNDWATER				
Culebra Boundary Conditions				
Recharge-Present and Future	Intermediate			
Recharge-Possible Ranges	Preliminary			
N/S Inflow/Outflow-Present/Future	Preliminary			
SW Inflow/Outflow-Present/Future	Preliminary			
Effect of Degraded Exploratory Borehole Casings	Preliminary			
Effect of Potash Mining	Preliminary			
Identify Past Boundary Cond/ Origin of Current System	Intermediate			
Integrate Geochemical/Isotopic Data	Intermediate			
Role of Culebra Fractures on Flow	Intermediate			
Radionuclide Solubilities in Culebra Brine	Preliminary			
Matrix/Fracture Porosity	Intermediate			
Variable Brine Density Effects				
Flow Potential	Intermediate			
Mixing	Preliminary			
Dissolution Processes	Advanced			
Compliance Assessment Module		Advanced	Advanced	Intermediate

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[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1] (continued)

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
(A) RADIONUCLIDE TRANSPORT IN NON-SALADO STRATA (continued)				
3-D GROUNDWATER				
Dewey Lake/Magenta Transmissivities	Preliminary			
Dewey Lake/Magenta Boundary Conditions	Preliminary			
Compliance Assessment Module		Intermediate	Intermediate	Preliminary
2-D TRANSPORT				
Matrix Retardation	Preliminary			
Fracture Retardation	Preliminary			
Compliance Assessment Module		Advanced	Advanced	Preliminary
3-D TRANSPORT				
Compliance Assessment Module		Preliminary	Preliminary	Preliminary
CLIMATE VARIABILITY				
Identification of Rainfall Changes	Intermediate			
Compliance Assessment Module		Preliminary	Preliminary	Intermediate
(B) FAR-FIELD BRINE INFLOW AND GAS DISSIPATION PROCESSES IN SALADO/CASTILE FORMATION				
2-PHASE GAS FLOW				
Extent of Interconnected Porosity	Preliminary			
Far-Field Pore Pressure and Distribution				
Anhydrite	Preliminary			
Halite: Pure/Argillaceous	Intermediate			

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[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1] (continued)

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
(B) FAR-FIELD BRINE INFLOW AND GAS DISSIPATION PROCESSES IN SALADO/CASTILE FORMATION (continued)				
Far-Field Permeability and Distribution				
Anhydrite	Preliminary			
Halite: Pure/Argillaceous	Intermediate			
Relative Permeability (to gas)				
Anhydrite	Preliminary			
Halite: Pure/Argillaceous	Preliminary			
Ideal Gas Solubility in Brine	Intermediate			
Gas Presently Dissolved Free in Formation	Preliminary			
Capillary Fingering	Preliminary			
Enhanced H_2 Diffusion in Halite/Anhydrite	Preliminary			
Threshold Pressure for Anhydrite Fracture Opening	Preliminary			
Darcy's Law vs. Stress Release of Brine	Preliminary			
Compliance Assessment Module		Intermediate	Preliminary	Preliminary
BRINE POCKETS				
Brine Pockets	Intermediate			
Compliance Assessment Module		Advanced	Intermediate	Intermediate
(C) WASTE PANEL				
CLOSURE AND COMPACTION				
Wall Closure (excluding DRZ)	Advanced			
Waste Compaction (Current Waste Type)	Intermediate			
Coupling of Components				
Wall Closure/Waste Compaction	Intermediate			
Wall Closure/Gas Generation/ Brine Behavior	Preliminary			

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[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1] (continued)

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
	(C) WASTE PANEL (continued)			
Compliance Assessment Module		Intermediate	Preliminary	Preliminary
DECAY MODEL				
CH-Waste Inventory				
Radionuclides	Intermediate			
RH-Waste Inventory				
Radionuclides	Preliminary			
Compliance Assessment Module		Advanced	Advanced	Intermediate
2-PHASE GAS AND RADIONUCLIDE TRANSPORT				
Inventory				
VOC	Preliminary			
Organics	Preliminary			
Al & Fe & Heavy Metals	Intermediate			
Gas Generation				
Corrosion	Preliminary			
Biological	Preliminary			
Radiolysis	Intermediate			
Gas Removal				
Flow into Salado	Preliminary			
Chemical	Intermediate			
Radionuclide				
Solubility	Preliminary			
Retardation	Preliminary			
Colloid Formation	Preliminary			
Fluid & Radionuclide Transport	Intermediate			
Marker Bed Transport and Storage	Preliminary			
DRZ: Transport & Storage	Preliminary			
Wall Closure/Gas Generation/ Brine Inflow	Intermediate			
Compliance Assessment Module		Preliminary	Preliminary	Preliminary

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[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1] (continued)

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
(C) WASTE PANEL (continued)				
HUMAN INTRUSION BOREHOLE				
Cuttings & Eroded Particles	Advanced			
Borehole Properties	Advanced			
Compliance Assessment Module		Advanced	Intermediate	Advanced
(D) WIPP SEAL SYSTEMS: DRIFT AND PANEL SEAL SYSTEM COMPONENTS				
PANEL SEAL				
Panel Seal				
Concrete Plug Member	Intermediate			
Grouting of Formation	Preliminary			
Preconsolidated Crushed Salt Backfill	Intermediate			
Drift: Preconsolidated Crushed Salt Backfill	Intermediate			
Compliance Assessment Module[2]		N/A	N/A	Intermediate
(E) WIPP SEAL SYSTEMS: SHAFT SEAL SYSTEM PRINCIPAL COMPONENTS				
SHAFT SEAL				
Water Bearing Zone Seal System				
Concrete Plug Members	Intermediate			
Grouting of Formation	Preliminary			
Clay Plug Members	Intermediate			
Upper Shaft Seal System				
Concrete Plug Members	Intermediate			
Grouting of Formation	Preliminary			
Clay Plug Members	Intermediate			
Compliance Assessment Module[2]		N/A	N/A	Preliminary

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[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-7. COMPLETENESS OF COMPUTATIONAL BASES FOR PERFORMANCE ASSESSMENT, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1] (concluded)

Compliance Assessment System: Conceptual Model of Component or Subsystem	Performance Assessment Understanding of Conceptual Model Uncertainty	Status of Performance Assessment Computer Model		Adequacy of Data for Performance Assessment
		Construction	Benchmarking	
(E) WIPP SEAL SYSTEMS: SHAFT SEAL SYSTEM PRINCIPAL COMPONENTS (continued)				
SALADO FORMATION				
Salado Formation				
Concrete Plug Members	Intermediate			
Grouting of Formation	Preliminary			
Clay Plug Members	Intermediate			
Lower Shaft Seal System				
Concrete Plug Members	Intermediate			
Grouting of Formation	Preliminary			
Clay Plug Members	Preliminary			
Preconsolidated Crushed Salt Backfill	Intermediate			
Compliance Assessment Module[2]		N/A	N/A	Preliminary

---

[1] Assumptions:
The repository is in an all-equilibrium condition, with no transient state in the first 100 years and no transient response following human intrusion.
No incremental compliance is required.
There will be no engineered modifications to the waste in the repository.

[2] N/A: Adequate models exist, but are yet to be incorporated into the CAS.

TABLE V-8. EARLY SEPTEMBER 1990 STATUS OF COMPOSITE PROGRAMS IN CAMCON

Code	Status	Work Remaining
1. GENMESH: rectilinear mesh generator	Done	
2. GENNET: network generator	Done	
3. FASTQ: finite element mesh generator	Working	Add records for CAMDAT format.
4. PATGEN: PATRAN to CAMDAT tranformation	Working	Add records for CAMDAT format.
5. PRELHS: pre-LHS translator	Done	
6. LHS: Monte Carlo sampling module	Done	
7. POSTLHS: post-LHS translator	Done	
8. MATSET: material property setup	Done	
9. PRESUTRA: pre-SUTRA translator	Working	Read time-dependent boundary conditions. Read source CAMDAT file.
10. SUTRA: hydrologic flow model	Working	Add time-dependent permeability and porosity capabilities. Add binary output.
11. POSTSUTRA: post-SUTRA translator	Working	Changes required by modifications to SUTRA.
12. PRESWIFTII: pre-SWIFTII translator	Working	Revise input format.
13. SWIFTII: hydrologic flow model	Done	
14. POSTSWIFTII: post-SWIFT translator	Done	
15. PREHST: pre-HST3D translator	Working	Quality assurance checkout.
16. HST3D: hydrologic flow model	Working	Add dynamic memory date and time. Add binary output.
17. POSTHST: post-HST3D translator	Working	Quality assurance checkout.
18. PRENEF: pre-NEFTRAN translator	Working	Changes required by modifications to NEFTRAN.
19. NEFTRAN: network transport model	Working	Add new source term. Add time-dependent boundary conditions.
20. POSTNEF: post-NEFTRAN translator	Working	Changes required by modifications to NEFTRAN.
21. PREBOAST: pre-BOAST translator	Working	Add capability to read table values from CAMDAT.
22. BOASTII: black oil model	Working	Add Darcy and interstitial velocity to output.
23. POSTBOAST: post-BOAST translator	Done	
24. SECO: hydrologic flow model	Working-Vrsn 2.0	Add multigrid solver.
25. STAFF2D: finite-element transport model	Working	Add multigrid solver. Add dynamic memory.
26. PRESTAFF: pre-STAFF2D translator	Done	

TABLE V-8. EARLY SEPTEMBER 1990 STATUS OF COMPOSITE PROGRAMS IN CAMCON (concluded)

Code	Status	Work Remaining
27. POSTSTAFF: post-STAFF2D translator	Done	
28. SUTRAW/G: SUTRA modified for fluid as gas instead of liquid	Working	Complete documentation.
29. PANEL: panel model	Prototype built	Add brine pocket model.
30. CUTTINGS: evaluation of amount of material removed during drilling	Working	Complete documentation and quality assurance checkout.
31. CCDFCALC: CCDF calculation program	Working	Improve table output. Add capability to calculate scenario complementary cumulative distribution function (CCDF).
32. CCDFPLOT: plots CCDF	Working	Add capability to plot scenario CCDF.
33. TRACKER: particle tracking support program	Working	Add three-dimensional capability.
34. ALGEBRA: CAMDAT manipulation program	Done	
35. BLOT: mesh and curve plotting	Working	Add capability to plot geographical data.
36. RELATE: interpolation from coarse to fine mesh and fine to coarse mesh (relates Property and boundary conditions)	Under dvlpmt	
37. GRIDGEOS: interpolation from data to mesh	Working	Check out kriging.
38. SUMMARIZE: multiple CAMDAT summary	Under dvlpmt	
39. UNSWIFT: converts SWIFT input files into CAMDAT	Under dvlpmt	
40. PRESTEP: pre-STEPWISE translator	Done	
41. STEPWISE: statistical module	Done	
42. PREPCC: pre-PCC/SRC translator	Done	
43. PCC/SRC: statistical module	Done	
44. CAM2TXT: binary CAMDAT to ASCII conversion	Working	
45. TXT2CAM: ASCII to binary CAMDAT conversion	Working	
46. GENPROP: item entry into property data base	Done	
47. FORTLISTING: lists programs & subroutines; summarizes comments & active FORTRAN lines	Done	
48. CHANGES: records needed enhancements to CAMCON or codes	Working	Add capability to automatically generate form.
49. HLP2ABS: converts help file to software abstract	Working	Switch over to INGRES data base format.

VI. CONTAINMENT REQUIREMENTS

The text of Chapter VI is preceded by a synopsis that simplifies concepts presented in Chapter VI. Detailed information about those concepts is in the text following the synopsis.

Synopsis

The Containment Requirements set limits on the amounts and associated probabilities of cumulative releases of radionuclides to the accessible environment for a period of 10,000 years after disposal.

Results presented here are not suitable for final compliance evaluations.

The results address:

Sensitivity of the modeling system to uncertainty in scenario probabilities.

Sensitivity of the modeling system to uncertainty in conceptual models with respect to transport of radionuclides and multiple intrusions.

Sensitivity of the modeling system to a hypothetical waste modification that reduces waste permeability and porosity and increases shear strength of the waste.

The effect of gas generation within the repository. Simulations that incorporate gas are preliminary, and cannot be used to quantify sensitivity of the modeling system to gas generation.

Results do not include potential effects of climatic change or subsidence outside the controlled area.

Modeling assumptions that are based on interpretations of the Standard are described in Chapter II.

Sensitivity analyses were performed using methods described in Chapter III.

The simulations consider the four scenarios described in Chapter IV: the undisturbed base case and the intrusion scenarios E1, E2, and E1E2.

Computer programs used were described in Chapter V.

Sensitivity to Scenario Probability Assignment

Simulations compare two preliminary sets of probabilities for the four scenarios and provide a qualitative measure of the degree to which scenario probabilities may influence predicted performance.

Simulations

Assume transport within the Culebra Dolomite Member occurs in clay-lined fractures.

Do not include the effects of gas pressurization.

Do not assume multiple intrusions other than the E1E2 scenario.

Results show

A significant difference in the mean CCDF curve between the two sets of probability assignments, indicating that the modeling system is sensitive to scenario probabilities.

Sensitivity to Model for Transport of Radionuclides

Simulations compare two conceptual models for transport of radionuclides within the Culebra Dolomite Member.

For one simulation, transport occurs only in fractures, and movement of radionuclides is retarded by the clays lining the fractures.

For the second simulation, transport occurs in a dual-porosity medium, and movement of radionuclides is also retarded in matrix porosity.

Simulations do not consider gas pressurization or multiple intrusions other than the E1E2 scenario.

Results show

Lower predicted releases with a dual-porosity model.

Greater retardation of radionuclides in the dual-porosity medium, so that direct releases at the ground surface become relatively more important.

Sensitivity to Multiple Intrusion Events

Simulations incorporating the possibility of multiple intrusion events other than E1E2 compare predicted performance using clay-lined-fracture and dual-porosity transport models. Gas-free conditions are assumed, and a specified probability model is assumed for number of intrusions in 10,000 years.

Results indicate that

> Because the sample resulted in more total intrusions, the probability of some releases increased.
>
> Because intrusions did not occur simultaneously (in contrast to the E1E2 scenario) and because brine flow was no longer arbitrarily forced through the waste panels (in contrast to the E1E2 scenario), other releases decreased.

Sensitivity to Waste Modification

Two simulations compare predicted performance with and without modifications to the waste form. The possibility of multiple intrusion events other than E1E2 is incorporated by sampling a probability model for number of intrusions.

Waste modification is simulated using modified values for waste permeability, porosity, and critical bulk shear strength. These values correspond to hypothetical properties of combustible and metallic waste that has been shredded, mixed with crushed salt to reduce void space, and repackaged in new containers.

Results suggest that

> For potential benefits from waste modification to be significant, waste permeability should be reduced to levels below those considered for these analyses.

Analyses of Modeling System Sensitivity to Parameter Uncertainty

Uncertainties in parameter values can affect results of the simulation. Parameter uncertainties can reflect natural parameter variability or the incompleteness of the data base.

A separate statistical analysis indicates that, for simulations of both E1 and E2 intrusions using the present modeling system and the assumed distributions for parameter values,

Uncertainty in the solubility of radionuclides dominated variability in cumulative subsurface releases. No other variable contributed significantly to the overall variation.

Borehole diameter uncertainty and time of intrusion dominated overall variability for simulations of only direct releases at the ground surface during drilling.

The simulations including both surface and subsurface releases were sensitive to uncertainty of all three parameters.

Preliminary Simulations Incorporating Gas Generation

Preliminary simulations with multiphase models examined the effect of gas generation in the waste on flow of brine and gas into an intruding borehole.

Results are conditional on the assumed parameter distribution and simplified models.

Results suggest

In the undisturbed state, gas could migrate several kilometers from the repository along MB139 and the anhydrite layers A and B.

Following intrusion, brine flows into the borehole only if permeability of the anhydrite layer is high. Factors controlling brine flow (and therefore radionuclide transport) include anhydrite permeability, capillary pressure, and gas-generation rate.

The Containment Requirements of the Standard state that disposal systems

> shall be designed to provide a reasonable expectation, based upon performance assessments, that the 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 quantities calculated [as specified]. (§ 191.13(a))

As indicated in Chapters II and III, in the final *Comparison*, compliance with the Containment Requirements will be evaluated using a mean CCDF curve that graphs probability versus cumulative radionuclide release for all significant scenarios. As discussed further in Chapter X, results presented here are not suitable for final compliance evaluations because portions of the modeling system and data base are incomplete, conceptual model uncertainties are high, final scenario probabilities remain to be determined, and the level of confidence in the results remains to be established. Uncertainty analyses required to establish the level of confidence in results will be included in future performance assessments as advances permit quantification of uncertainties in the modeling system and the database.

Preliminary performance assessments use mean CCDF curves to examine sensitivity of the modeling system to specific uncertainties. As discussed in Chapter III, these sensitivity analyses are performed *ceteris paribus*, and all input except that being examined in the analyses is the same in all directly compared simulations. Results presented here address sensitivity of the modeling system to uncertainty in scenario probabilities, and uncertainty in conceptual models for radionuclide transport, gas-pressurization effects, and multiple intrusions. Results also examine the effect of a hypothetical waste modification on predicted performance, assuming the occurrence of multiple intrusions. Modified-waste parameter values correspond to the estimated properties of combustible and metallic waste that has been shredded, mixed with crushed salt to reduce void space, and repackaged. Modifications, analogous to this hypothetical example, that lower permeability within the waste panel could be used if necessary to reduce brine flow through the waste and radionuclide dissolution (U.S. DOE 1990d). Potential benefits of reducing gas-generation rates through waste modification are not considered in these analyses, but will be included in the 1991 performance assessment.

Simulations examining modeling system sensitivity *ceteris paribus* to multiple intrusions sample a Poisson distribution of intrusion events over 10,000 years, as described in Chapter IV. Other simulations use fixed scenario probabilities, also as described in Chapter IV. For all simulations, parameter values were sampled probabilistically as described in Chapter III, using distribution functions from Rechard et al. (1990b). Simulations of a fixed number of intrusion events used a sample size of 40; sample size for a variable number of intrusion events was 70. Parameter values sampled probabilistically are summarized in Appendix C. Fixed values for waste parameters are summarized in Table VI-1. Computer programs used were as described in Chapter V. SUTRA simulated brine flow into the waste panel, and PANEL simulated radionuclide dissolution and brine flow within the waste panel and boreholes. NEFTRAN simulated flow and transport for the undisturbed base case. For intrusion scenarios, SECO2D simulated both regional and local flow within the Culebra Dolomite Member of the Rustler Formation. For simulations including gas, the generation rate selected was the maximum expected hydrogen gas generation rate (Brush and Anderson, 1988b), and BOAST II and BRAGFLO simulated repository response. Radionuclide transport within the Culebra Dolomite Member, for both fractured and dual-porosity systems, was simulated with STAFF2D.

TABLE VI-1. PARAMETER VALUES USED FOR COMPARISON OF REFERENCE-DESIGN AND HYPOTHETICAL MODIFIED WASTE

Parameter/Units	Reference Value	Modified Value
Waste-Panel Permeability (m^2)	1×10^{-13}	2.4×10^{-17}
Waste-Panel Porosity	0.19	0.085
Waste-Panel Critical Bulk Shear Strength (Pa)	1	5

Source: Rechard et al., 1990b

Flow and transport within the borehole were not specifically included in intrusion simulations, and flux entering the Culebra Dolomite Member was assumed to be equal to flux entering the borehole from the repository. This assumption excludes possible retardation within the borehole fill, but does not exclude borehole-fill permeability and borehole diameter as controls on brine flow. Borehole parameters are included within SUTRA and PANEL, and limit flow entering the borehole from the repository. For those samples in which the pressure gradient between the waste panel and the Castile brine reservoir resulted in downward flow, releases were assumed to be zero.

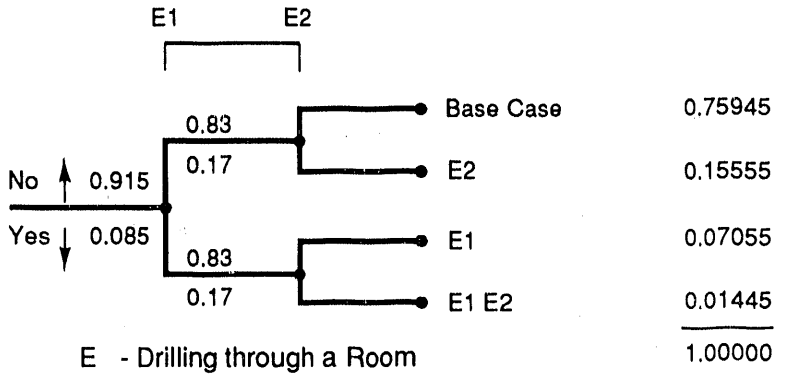
All results include integrated, cumulative 10,000-year releases in the subsurface 2.5 km (1.6 mi) downgradient from the waste panels. Mean CCDFs are calculated separately with and without direct releases at the ground surface during drilling; direct releases are determined using the borehole erosion model described in Chapter V. Simulations in progress include variable recharge to the Culebra Dolomite Member caused by climatic changes; results presented here, however, are calculated assuming recharge remains constant at current levels. Results presented here do not include effects of any local increases in recharge due to subsidence related to potential future potash mining outside the controlled area.

Sensitivity to Scenario-Probability Assignment

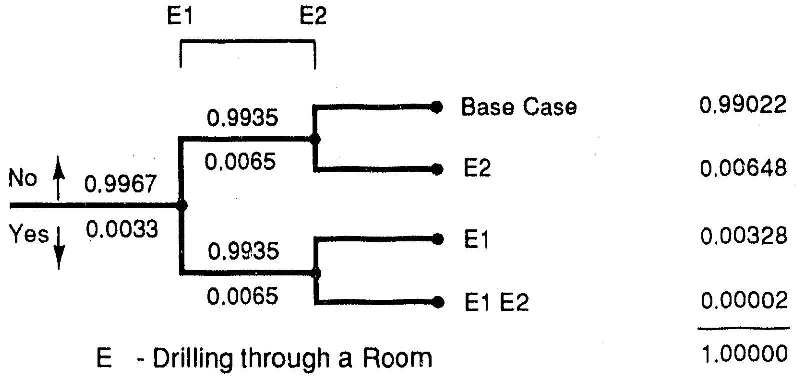
Simulations compare two sets of probabilities for the four scenarios and provide a qualitative measure of the degree to which scenario probabilities *ceteris paribus* may influence predicted performance. As described in Chapter IV, one set of probabilities is from Marietta et al. (1989) (Figure IV-9), and the other is that reported by Guzowski (in prep.) (Figure IV-8). Because the effects of subsidence are not considered in these simulations, the logic diagrams presented in Chapter IV have been simplified (Figure VI-1). The subsidence event, TS, is omitted, and the scenario probabilities are recalculated accordingly. Both sets represent possible probability assignments based on reasonable arguments. Neither set, however, is presented here as a final set of probabilities.

Calculations assume that transport within the Culebra Dolomite Member occurs in clay-lined fractures. Effects of gas pressurization are not simulated, and multiple intrusions other than the E1E2 scenario do not occur.

Results in Figure VI-2 show a distinct shift in the mean CCDF curve from the relatively higher-probability intrusions (Marietta et al., 1989) to the relatively lower-probability intrusions (Guzowski, in prep.). The probabilities of intrusion are 0.24 and 0.0098 and are derived from Figure VI-1a and Figure VI-1b. Those values correspond to the probability-axis intercepts of the mean CCDFs that include releases during drilling. The mean CCDFs without releases during drilling do not have the same probability-axis intercepts in Figure VI-2 because some of the summed normalized releases are less than 10^{-10}. Between Figures VI-1a and VI-1b, the probabilities of scenarios E1 and E2 both decrease by a factor of about 25, but the probability of scenario E1E2 decreases by a factor of about 500. The largest summed normalized releases for the mean CCDF calculated using the Figure VI-1a probabilities are dominated by subsurface releases from scenario E1E2 because of the arbitrary assumptions for borehole plugging and simultaneous intrusion times. Because the probability of this scenario decreased by 500,



a. Modified Scenario Probability Estimate, Based on Marietta et al., 1989.



b. Modified Scenario Probability Estimate, Based on Guzowski, in prep.

TRI-6342-768-0

Figure VI-1. Modified Scenario Probability Estimates Used in This Report. Probabilities of events E1 and E2 are as shown in Figure IV-7 and IV-8. The subsidence event TS has been removed from the diagrams, and scenario probabilities have been recalculated accordingly.

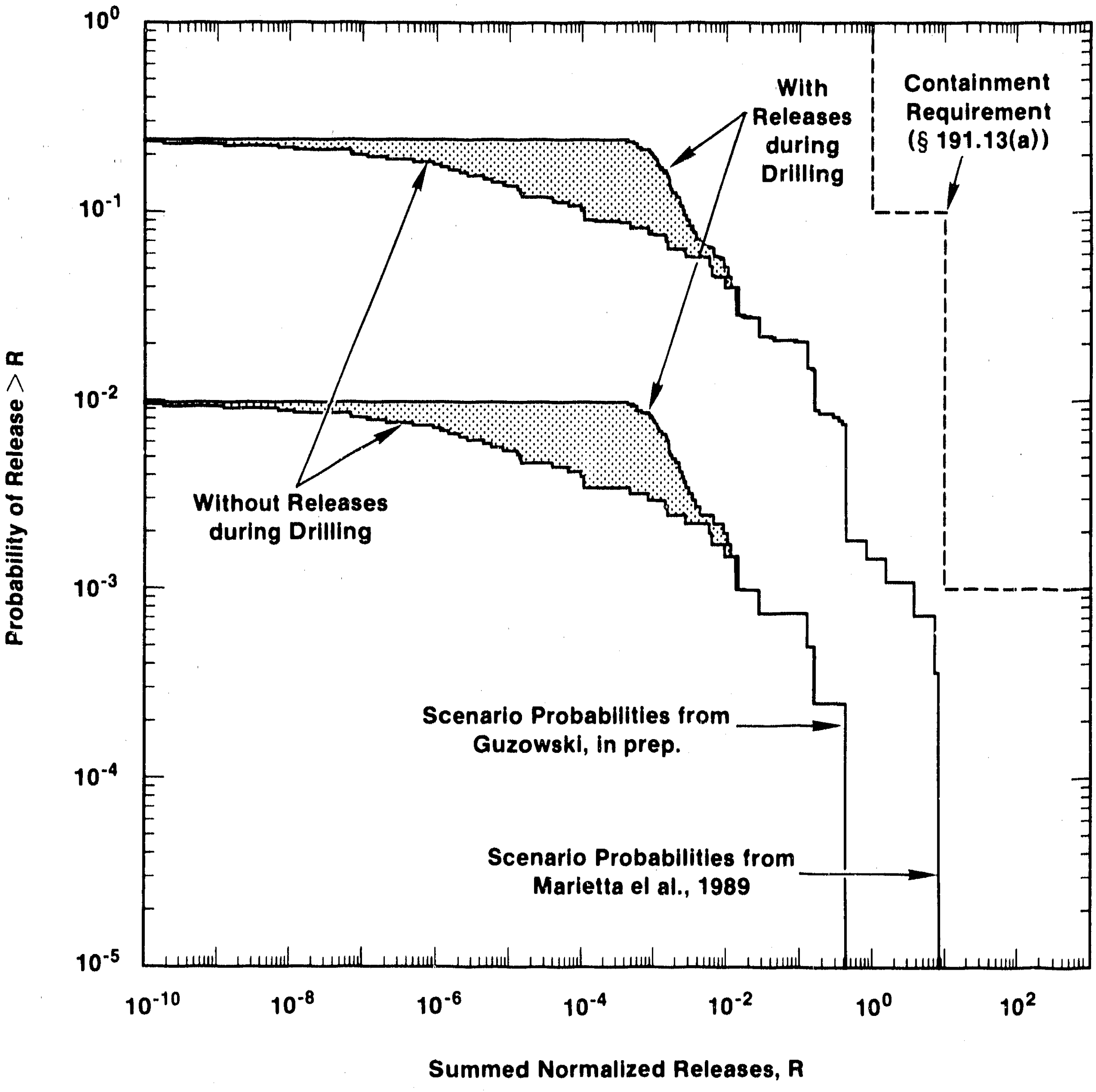


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Figure VI-2. Sensitivity Analysis Using Mean CCDF Curves to Compare Two Scenario Probability Assignments. Each curve was calculated separately with and without direct releases at the ground surface during drilling. The curves illustrate the potential uncertainty introduced by scenario probability assignments. Curves are based on 40 simulations each of the undisturbed base case and intrusion scenarios E1,E2, and E1E2. Scenario probabilities are modified from Marietta et al., (1989) and Guzowski (in prep.), as shown in Figure VI-1. Radionuclide transport is assumed to occur in clay-lined fractures only, and the repository is assumed to be gas-free. The undisturbed base case for these calculations does not include effects of climate change or of subsidence.

the probability of those releases is too small to plot on Figure VI-2. Overall, the mean CCDF is sensitive to scenario probabilities, and whether the performance prediction is adequate will depend in part on the level of confidence in probability estimates.

Results also indicate that, regardless of scenario probabilities, within the stippled areas (larger probability, lower cumulative sum releases) in Figure VI-2 the mean CCDF curves are sensitive to direct releases at the ground surface. For the fracture-flow transport model simulated here, cumulative releases with smaller probabilities (the lower portion of the mean CCDF curve) are less sensitive to direct releases, and the mean CCDFs calculated with and without direct releases converge as probability decreases.

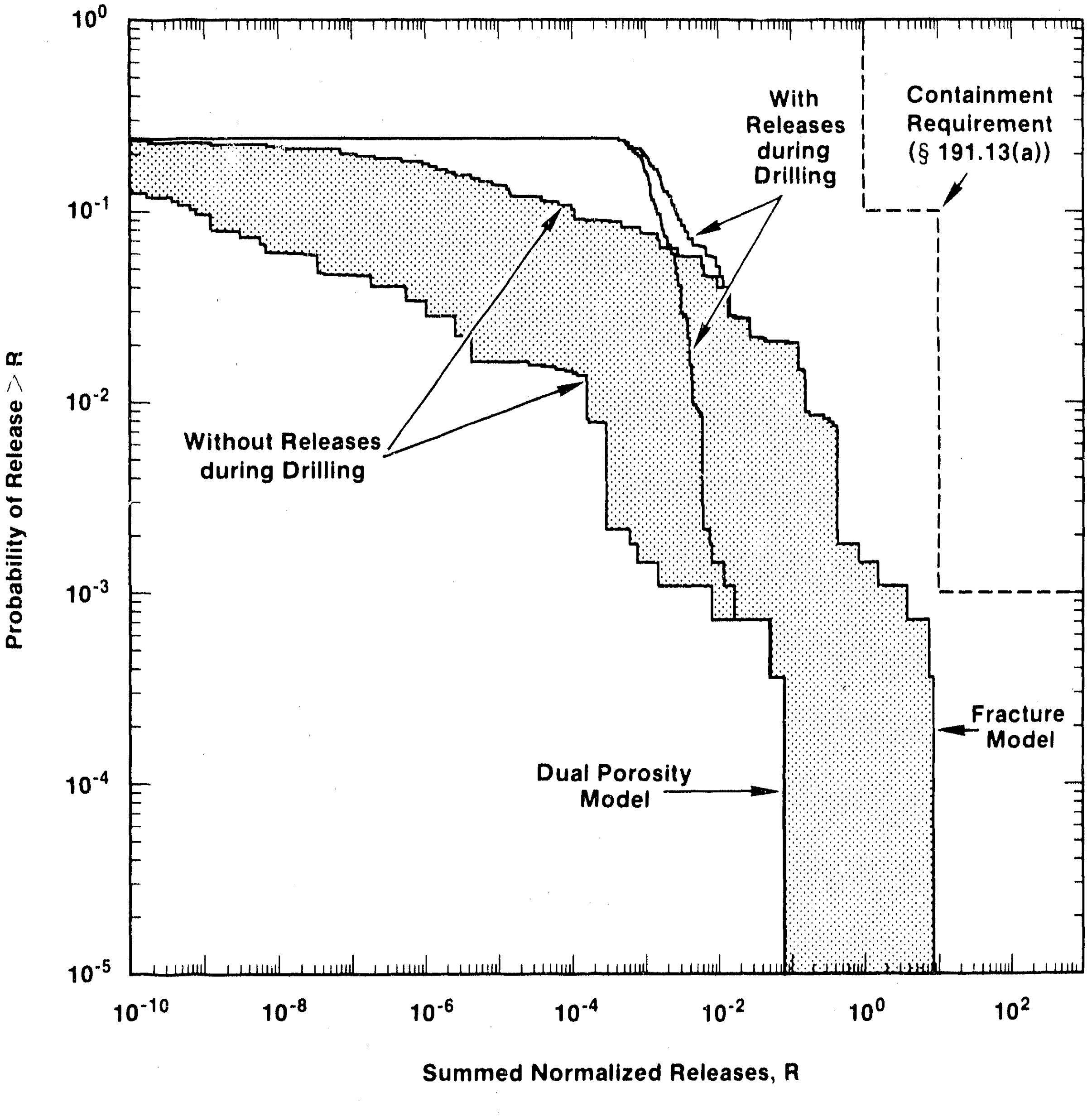
Sensitivity to Radionuclide-Transport Submodel

The simulations for Figure VI-3 compare two conceptual models *ceteris paribus* for radionuclide transport within the Culebra Dolomite Member of the Rustler Formation. Probabilities for both simulations are from Marietta et al. (1989). Neither simulation considers gas generation or multiple intrusions other than the E1E2 scenario. For one simulation, transport occurs only in fractures, and all radionuclide retardation is due to sorption by clays lining the fractures. This simulation is identical to the higher probability curve of Figure IV-1. For the second case, transport occurs in a dual-porosity medium, and retardation also occurs in the matrix porosity.

Results show a substantial shift of the mean CCDF curve toward lower releases with a dual-porosity model. With greater retardation in a dual-porosity medium, curves calculated with and without direct releases at the ground surface converge for the largest subsurface releases. Otherwise, results are dominated by direct releases. The stippled region in Figure VI-3 represents a measure of modeling uncertainty *ceteris paribus* for those two radionuclide-transport models considering only subsurface releases. Approaches for including modeling uncertainty in the 1991 performance assessment will be evaluated on a submodel by submodel basis. This submodel is only one example. The area between the two total release curves including releases during drilling (in part not stippled) represents a measure of modeling uncertainty for comparison to the Standard.

Sensitivity to Multiple Intrusion Events

Simulations incorporating the possibility of multiple intrusion events other than E1E2 compare predicted performance using clay-lined-fracture and dual-



TRI-6342-638-1

Figure VI-3. Sensitivity Analysis Using Mean CCDF Curves to Compare Dual-Porosity and Fracture Models for Radionuclide Transport. Each curve is calculated separately with and without direct releases at the ground surface during drilling. The area between the curves is a measure of the potential uncertainty introduced by the choice of these specific submodels. Curves are based on 40 simulations each of the undisturbed base case and intrusion scenarios E1, E2, and E1E2. Scenario probabilities are from Marietta et al. (1989). The repository is assumed to be gas-free. The undisturbed base case for these calculations does not include effects of climate change or of subsidence.

porosity transport models (Figure VI-4). Gas-free conditions are assumed. As described in Chapter IV, a Poisson distribution is arbitrarily assumed for number of intrusions in 10,000 years (Tierney, in prep.).

The Poisson distribution for multiple intrusions is sampled by drawing a uniformly distributed random variable U from the unit interval during the sampling. If the conditional Poisson distribution function is denoted by q_n, the number of intrusions for the sample is determined to be one if $U < q_1$, two if $q_1 < U < q_1+q_2$, three if $q_1+q_2 < U < q_1+q_2+q_3$, and so on.

To obtain the time of these n events for one sample, n uniformly distributed random variables U_i are drawn from the unit interval. The ordered times U_iT, where T is the time period during which the n events take place (10,000 years in this case) are the event times. For convenience, because the intrusion events are assumed to occur independently at a maximum rate of 15 per 10,000 years based on the Standard, 15 samples are drawn, and the earliest n are taken for the event times.

Three types of events affect the consequence calculation. E1 and E2 are two of these events. The third is an intrusion event into a previously intruded panel, differing from E1E2 in the possibility of more than two intrusions into the same panel, in any combination of E1s and E2s. To determine the type of event, a uniformly distributed, discrete random variable (144 possible values) is sampled for each event. Each variable value represents a location in the repository waste panels. If the location overlies Castile brine, the event is an E1. If the location does not overlie Castile brine, the event is an E2. Each sample can be inspected to see how many times the same panels are intruded. The calculations for multiple intrusions into the same panel are then defined by the combination of E1s and E2s and their times of occurrence. Definitions for the 70 samples are given in Appendix C.

Direct overlays of Figure VI-4 with the mean CCDF curves based on the E1, E2, and E1E2 scenarios are not appropriate because the simulations reflect different Latin hypercube samples drawn from a different set of parameter values (see Appendix C). However, comparison of Figure VI-4 with Figure VI-3 indicates that the assumption of a Poisson distribution for multiple intrusion events increases the frequency of cumulative releases that have large probabilities. This increase corresponds in large part to an increase in the probability of intrusion relative to the subjective probability assignment from Marietta et al. (1989). The larger cumulative releases with small probabilities are less for the multiple intrusion simulation, however, than the comparable releases calculated using the assigned scenario probabilities from Marietta et al. (1989).

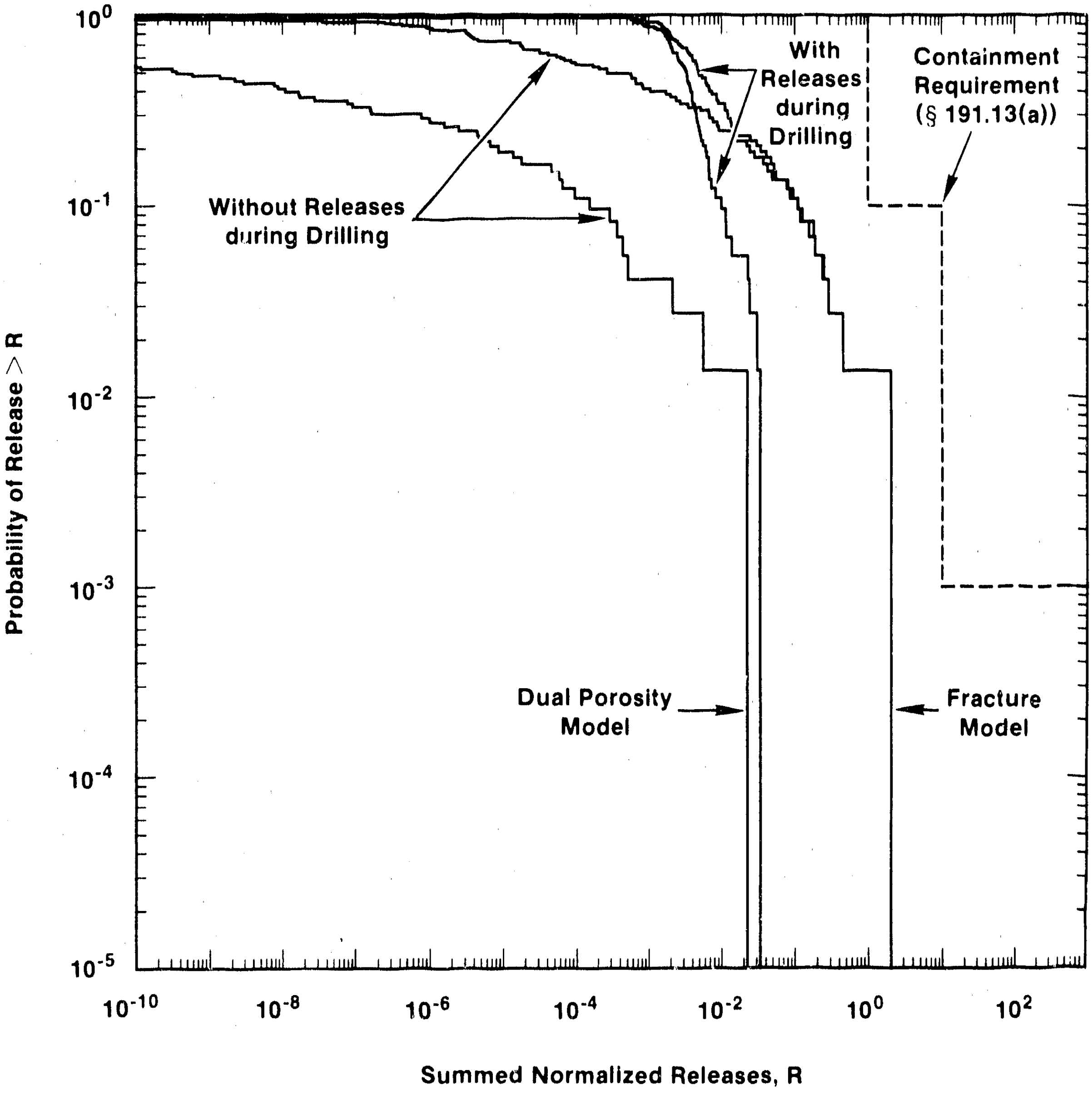


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Figure VI-4. Sensitivity Analysis Using Mean CCDF Curves Calculated Assuming a Poisson Distribution for Number of Intrusions in 10,000 Years, Comparing Dual-Porosity and Fracture Transport Models. Each curve is calculated separately with and without direct releases at the ground surface during drilling. The repository is assumed to be gas-free. The undisturbed base case for these calculations does not include effects of climate change or of subsidence.

Qualitatively, this result suggests that scenario E1E2, which accounts for a significant fraction of the cumulative releases with small probabilities in the three-scenario simulations, causes greater cumulative releases than the E1E2-like intrusion events that result from the sampling of the Poisson distribution. In part, this conservatism is inherent in the assumption that the E1 borehole in the E1E2 scenario is plugged completely between the repository and the Culebra Dolomite, forcing all upward flow to move through the waste panel and up the E2 borehole. In the multiple intrusions simulated here, all holes are assumed to contain degraded plugs below the Culebra Dolomite, and the flow path is not arbitrarily constrained below the Culebra. As in all scenarios considered in this assessment, borehole plugs above the Culebra Dolomite remain intact, forcing all flow into that unit. As in all scenarios except E1E2 boreholes below the Culebra Dolomite are assumed to creep partially closed. No allowance is made for the possibility that anisotropy in the salt may cause complete creep closure.

The assumption that both holes are drilled simultaneously adds additional conservatism to the E1E2 scenario. As shown in Figure VI-1 and Table C-4 of Appendix C, the Poisson distribution sample resulted in a larger overall probability of multiple intrusions (0.03 for E1E2-like intrusions versus 0.01445 for E1E2 based on the probabilities of Marietta et al., 1989), but because the time of intrusion for E1 and E2 was sampled independently, few E1 and E2 events occurred close together in time within a single panel. For E1 and E2 intrusions into the same panel at different times (noted in Table C-4 of Appendix C as having a pattern resembling E1E2), predicted releases decrease as the time between intrusion events increases if one event is sufficiently close to the 10,000-year limit. Overall, cumulative releases with small probabilities from E1E2-like events dropped accordingly.

Comparison of the multiple-intrusion simulations assuming either the dual-porosity or clay-lined-fracture transport model shows results similar to those of Figure VI-3. Greater retardation within the dual-porosity medium results in predicted releases smaller than those predicted assuming transport occurs only in clay-lined-fractures. As in the case with assigned scenario probabilities (Figure VI-3), the dual-porosity curves are dominated by direct releases during drilling. This result in part reflects an increase in the total number of intrusions. The maximum number of boreholes in Table C-4 is 9 (vector number 35). One 8, two 7s, and five 6s also occur. Nine releases during drilling must be summed for vector 35, and similarly for the others. For this one LHS-replicate, releases during drilling result in larger summed normalized releases than the corresponding subsurface releases because some intrusion events are sufficiently close to 10,000 years that subsurface releases do not occur.

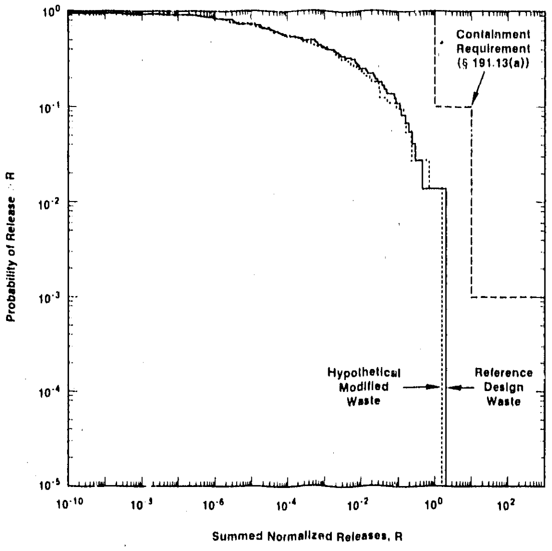
Sensitivity to Waste Modification

Two simulations compare predicted performance with and without the waste form being modified (Figure VI-5). The possibility of multiple intrusion events other than E1E2 has been incorporated by sampling on number of intrusions using a Poisson distribution as described in the preceding section. Waste modification is simulated by modifying values for waste permeability, porosity, and critical bulk shear strength corresponding to hypothetical properties of combustible and metallic waste that has been shredded, mixed with crushed salt to reduce void space, and repackaged in new containers (Table VI-1). Transport within the Culebra Dolomite occurs in clay-lined fractures only. Effects of gas pressurization are not included.

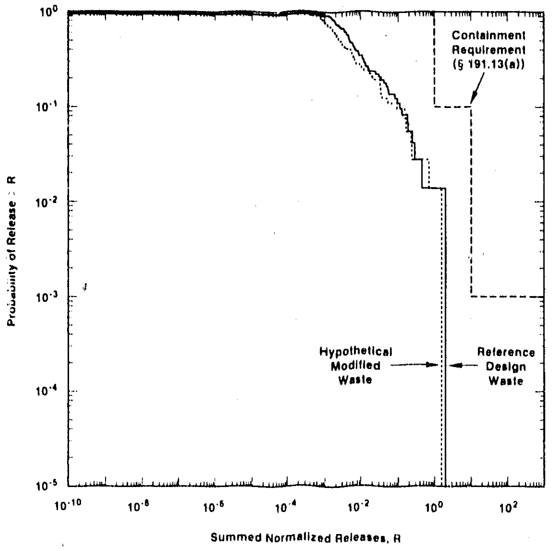
Results presented in Figure VI-5 indicate that, within the range of waste parameter values considered, modifications in waste form have relatively little effect on simulated performance. Except for the larger-probability portion of the curve where critical bulk shear strength affects direct releases, waste permeability provides the principle control on the calculated results. As shown in Figure VI-6, flux entering the borehole, as simulated using SUTRA, is strongly dependent on waste permeability only at low permeabilities (Rechard et al., 1990a). At higher permeabilities, including the range examined here, flux is limited by the rate of brine inflow from the Salado Formation rather than by waste permeability, and even relatively large changes in waste permeability result in little change in flux. At all permeabilities, flux is dependent on pressure.

The effect of relatively small changes in flux entering the borehole is obscure on the logarithmic scale of the mean CCDF curve. Figure VI-7 shows integrated flux as a function of time after intrusion for the reference-design and hypothetical modified waste. Flux is relatively high during the first millenium and then decreases as salt creep decreases the borehole diameter. Comparison of the two curves shows that flux through this hypothetical modified waste is approximately 70 percent of flux through reference-design waste.

Results of this sensitivity analysis do not support conclusions about either the potential effectiveness of engineered modifications to the waste form or the need for such modifications. The results do suggest, however, that for modifications to be effective, permeability in the room must be reduced until the permeability becomes effective in limiting flux into the borehole. Present modeling suggests that reductions in room permeability below approximately 10^{-17} m^2 (10^{-2} md) will achieve that result.



a. Without direct releases at the ground surface during drilling.



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b. With direct releases at the ground surface during drilling.

Figure VI-5. Sensitivity Analysis Using Mean CCDF Curves to Compare Reference-Design and Modified Waste, Calculated Assuming a Poisson Distribution for Number of Intrusions in 10,000 Years. Radionuclide transport is assumed to occur in clay-lined fractures only, and the repository is assumed to be gas-free. The undisturbed base case for these calculations does not include effects of climate change or of subsidence. Modified waste permeability, porosity, and critical bulk shear strength correspond to hypothetical properties of combustible and metallic waste which has been shredded, mixed with crushed salt to reduce void space, and repackaged.

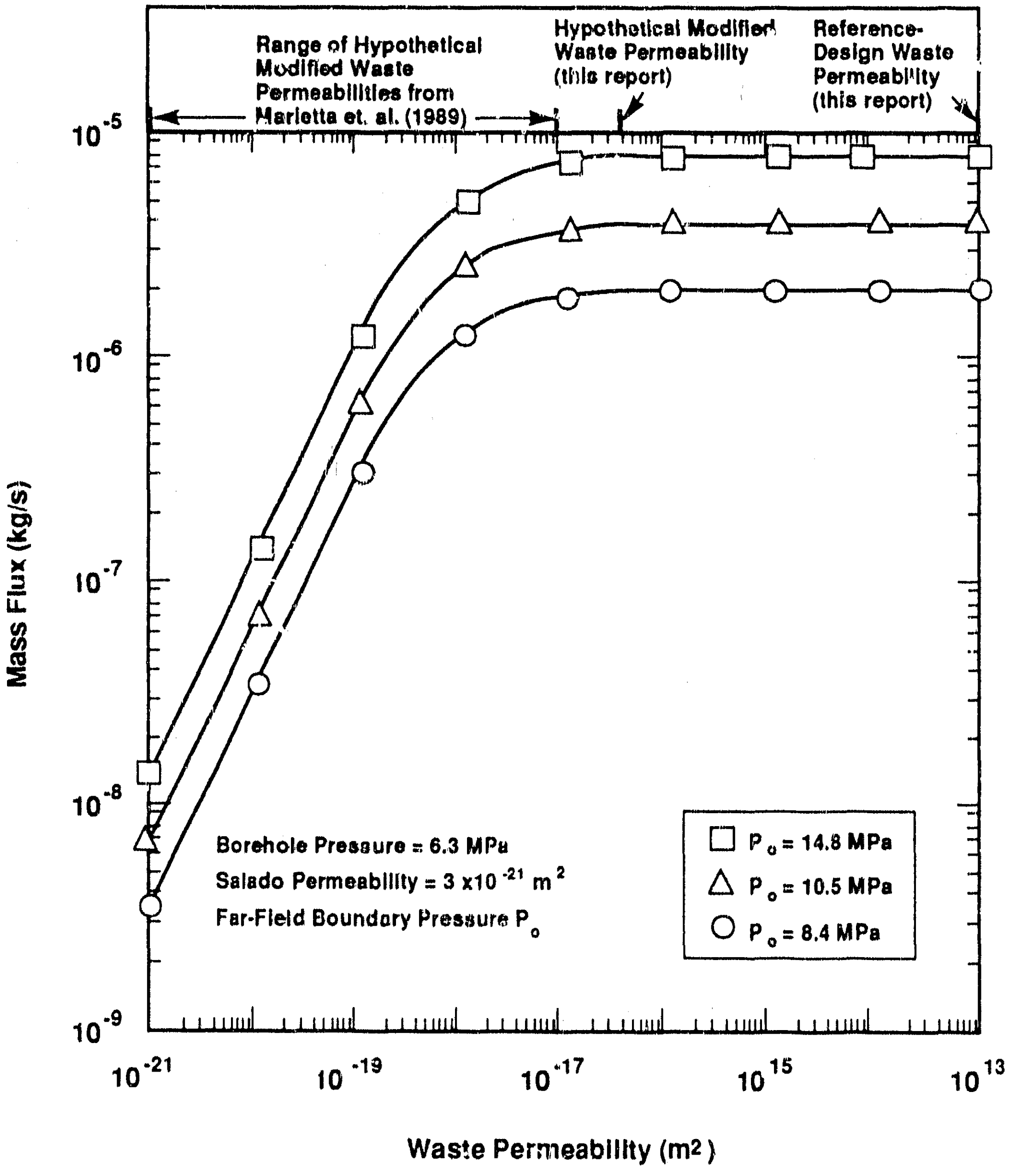

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Figure VI-6. Variation of Mass Flux to a Borehole as a Function of Waste Permeability at Several Pressure Gradients, Assuming Steady-State Conditions (Rechard et al., 1990a, Figure 4.2). Because mass flux is dependent on pressure and distance to boundary, only relative changes (not absolute values) are meaningful. Permeabilities used in Figure VI-5 for reference-design waste and modified waste are indicated. Ranges of permeabilities used by Marietta et al. (1989) are also indicated.

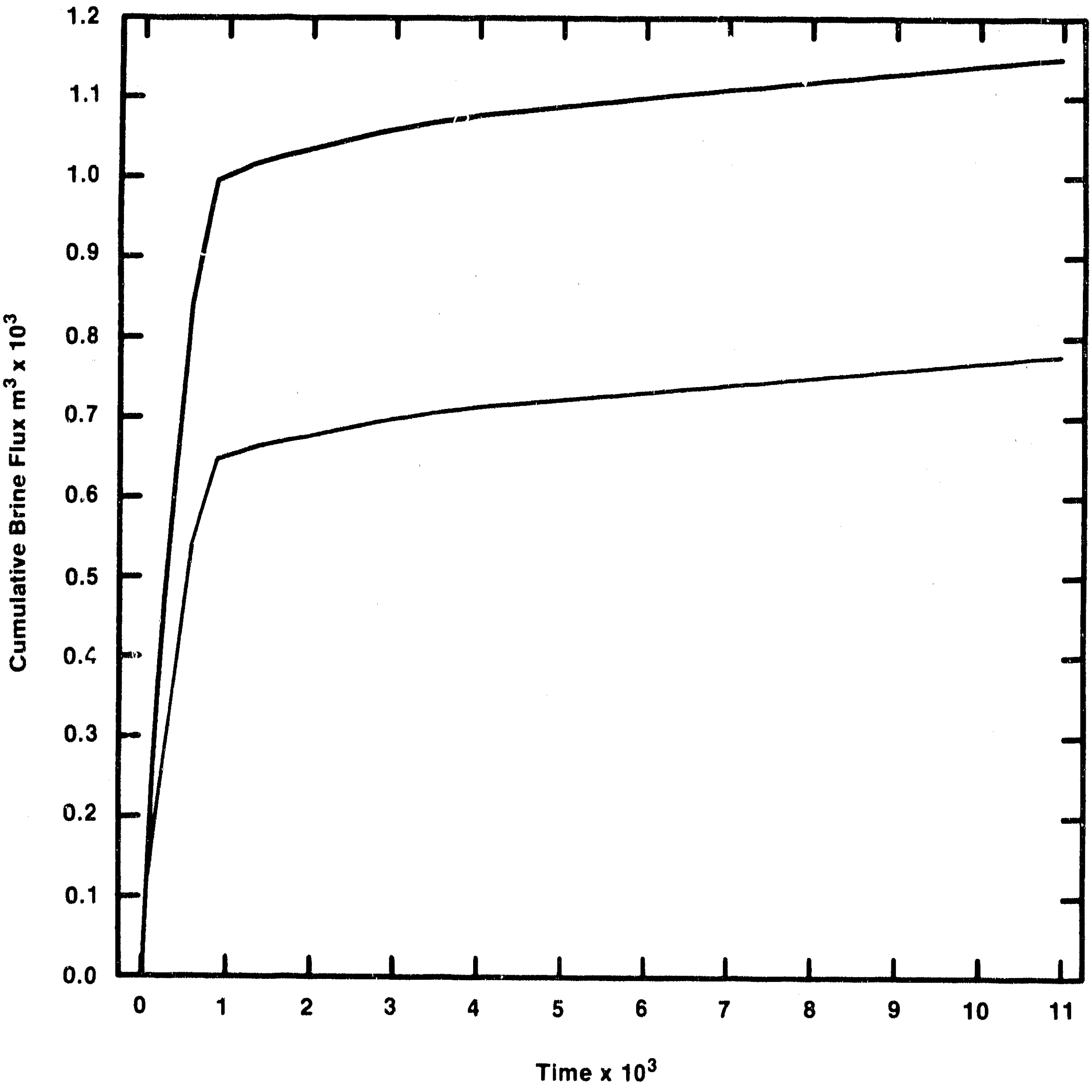

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Figure VI-7. Comparison of Integrated Flux to a Borehole Calculated For Reference-Design and Modified Waste Permeabilities. Cumulative flux increases rapidly in the first millennium after intrusion, then increases more gradually as borehole diameter is reduced by salt creep. Flux through modified waste is approximately 70 percent of flux through reference-design waste: the reduction does not result in a significant shift in the logarithmic CCDF curves shown in Figure VI-5

Analyses of Modeling System Sensitivity to Parameter Uncertainty

Simulations summarized in the preceding sections addressed sensitivity of the modeling system *ceteris paribus* to scenario probabilities and conceptual model uncertainties. Uncertainties in parameter values also affect simulation results. Parameter uncertainties may reflect natural parameter variability or the incompleteness of the data base.

Helton (1990) examined modeling system sensitivity to uncertainty in 29 selected parameters using stepwise regression analysis of single-scenario simulations for E1 and E2. All results are conditional on the assumed fracture-transport and gas-free models, and use current estimates for parameter value distributions. Results indicate that for simulations of subsurface releases resulting from either E1 or E2 intrusions, uncertainty in radionuclide solubility dominated variability in the normalized cumulative releases. No other independent variable made substantial contributions to the overall variation in releases. Direct releases at the surface during drilling were dominated by borehole diameter and time of intrusion. Combined simulations including both surface and subsurface releases were sensitive to uncertainty in all three parameters.

Sensitivity analyses on parameter uncertainty indicate that significant variability can result from uncertainty in radionuclide solubility, borehole diameter, and the time of intrusion. Effects of solubility uncertainty may be somewhat overestimated because a single distribution of solubilities has been used for all radionuclides, increasing the likelihood that this parameter will be correlated with cumulative releases (Helton, 1990).

Preliminary Simulations Incorporating Gas Generation

Preliminary simulations with multiphase models examined what effect gas generation in the waste has on flow of brine and gas into an intruding borehole. Simulations in progress will examine the effect of gas generation on the mean CCDF. The influence of gas-generation rates, interbed permeability, and interbed capillary pressure was investigated. These calculations are intended to assess modeling uncertainty between single-phase and two-phase Darcy flow models for the repository.

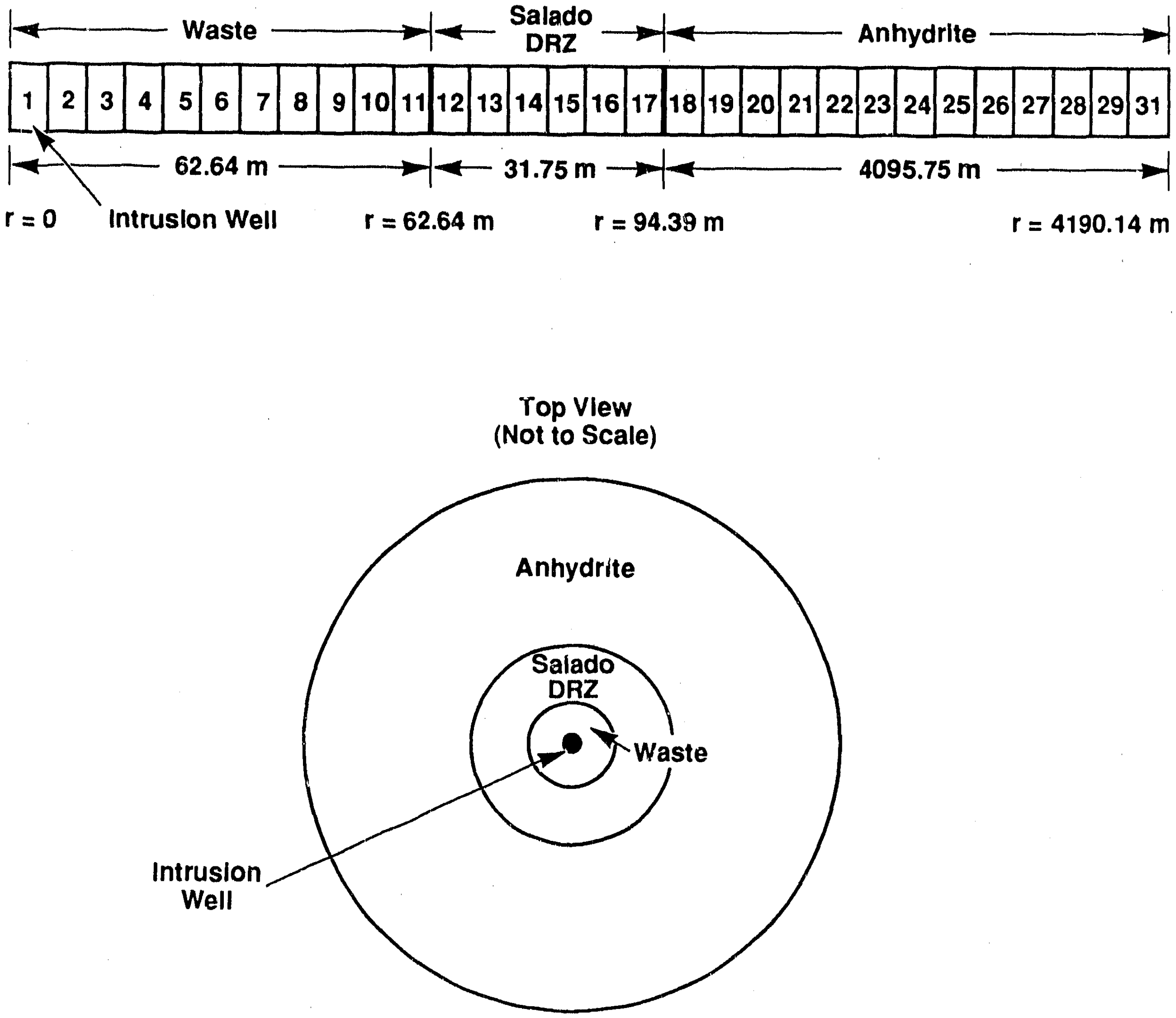
A complete analysis to construct mean CCDFs with the two-phase Darcy-flow model included in the CAMCON system was not performed because of the slow execution speeds of available programs. Instead, one input vector that is representative of a computationally difficult set of material properties was constructed for subsidiary calculations.

Two programs were used: BOAST II and BRAGFLO. BOAST II cannot model converging flow of brine to a borehole because the rapidly changing saturations cause instabilities in the implicit-pressure, explicit-saturation procedure. BOAST II is well suited, however, for simulating the non-intrusion scenarios in multiple dimensions. The intrusion scenario was initially set up as a two-dimensional problem using BOAST II. This scenario was simulated until the borehole plugs degraded sufficiently to allow flow up the borehole. For simulations beyond this point, BRAGFLO was used. This program has not been verified yet in two dimensions, so a series of one-dimensional simulations was done using BRAGFLO to approximate the two-dimensional geometry in the BOAST II and SUTRA simulations.

An equivalent panel was modeled in cylindrical geometry as a disk, with the intrusion borehole at the axis of symmetry. The region modeled is the same as that shown in two dimensions in Figure V-32. The one-dimensional geometry of the model differs from that for the SUTRA simulations used to construct the CCDF curves shown in Figures VI-2 through VI-5.

A one-dimensional mesh (Figure VI-8) condensed the two-dimensional mesh. BOAST II simulations indicated that the primary gas flow path was through the waste, up through the DRZ, and out through the combined anhydrite A and B layer. The one-dimensional mesh approximates that flow path, while assuming a cylindrical geometry, so that the storage capacity of the formations increases as the square of the distance from the axis of symmetry. The outer radius of the first two sections is 94 m (308 ft), which is the radius of a cylindrical equivalent-area panel. This mesh is not an exact representation of the two-dimensional mesh. The panel volume is smaller, and the DRZ is longer than in the two-dimensional mesh. The radial distance to the anhydrite layer, a key dimension in the two-dimensional model, was preserved. The greater length of the DRZ helps to compensate for the reduced storage capacity in the one-dimensional mesh compared to the two-dimensional mesh. The thickness of the anhydrite layer is 2 m (6.6 ft) in the one-dimensional mesh, compared to a total (of both the anhydrite layer and MB139) of 1.2 m (3.9 ft) in the two-dimensional mesh; because the thickness of the grid could not be varied, the waste panel thickness was preserved rather than the thickness of the anhydrite layer. One other important shortcoming of the one-dimensional model is that flow from the Salado Formation could not be simulated because there is only one layer. Brine can flow only from the constant-pressure source in the outermost block.

The one-dimensional simulations cannot be compared with any particular vector in the SUTRA simulations, because none of the properties sampled in the multiple-vector simulations were used in the one-dimensional model. For example, Salado permeability and compressibility and borehole permeability were sampled in the SUTRA two-dimensional simulations. The one-dimensional



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3 Figure VI-8. One-Dimensional Mesh for BRAGFLO Calculations.

model includes neither the Salado Formation nor a borehole represented by a region of blocks. One-dimensional simulations should be compared, therefore, to SUTRA simulations that used a high borehole permeability and low Salado permeability.

TWO-PHASE SIMULATIONS

Results from one two-dimensional BOAST II simulation illustrate the direction and extent of gas flow during the gas-generation phase, prior to the opening of the borehole. A total of six one-dimensional simulations were carried out using BRAGFLO: a base case taken from the above 40 vector analyses (Table C-2, Appendix C) and five variations. The entire 10,000-year assessment period, including the gas-generation period and the borehole intrusion, was simulated. The important properties of each modeled region are listed in Table VI-2.

BOAST II Simulations

The BOAST II simulation was run out to 1216 years, when the intruding borehole opens in vector 26. Results are shown in Figures VI-9 through VI-12. Figure VI-9 shows gas saturation contours at 713 years, when all gas generation is assumed to end (Rechard et al., 1990b). The figure shows only the region near the waste panel wall. Contours extend horizontally beyond the edges of the figure to the axis of symmetry far to the left and to the computational domain boundary, about 4 km (2.5 mi) to the right. The figure shows the upper half of the panel is largely gas saturated. Brine has drained by gravity to the lower half of the panel. Gas also saturates the DRZ above the panel, and has opened flow paths to both the anhydrite layer above the panel and into MB139 below the panel. Note that MB139 beneath the panel remains saturated with brine. Gas penetrates MB139 only beyond the panel. Figure VI-10 shows gas saturation contours at 1216 years, after the 1000-year period of the Individual Protection Requirements. After gas generation ceases, pressure and phase distributions gradually equilibrate throughout the entire region. Gas continues to expand outward, while brine flows in. The brine flows primarily along the lower portions of the anhydrite and MB139. Gas saturation in MB139 near the waste panel diminishes considerably from 713 years to 1216 years (Figure VI-10). This drop in gas saturation is illustrated more clearly in Figure VI-11, which shows gas saturation profiles along the top of MB139 at various times. Figure VI-12 shows gas saturation profiles at the same times in the anhydrite layer. This figure indicates that the anhydrite layer is a major flow path for the outwardly expanding gas. The layer remains largely gas-saturated adjacent to the waste panel, and continues to provide a path for gas and brine flow. In contrast, brine cuts off the gas-flow path near the waste in MB139, inhibiting return flow of gas to the waste when a borehole opens and

TABLE VI-2. MATERIAL PROPERTIES FOR TWO DIMENSIONAL (BOAST II) SIMULATIONS OF GAS-GENERATION EFFECTS

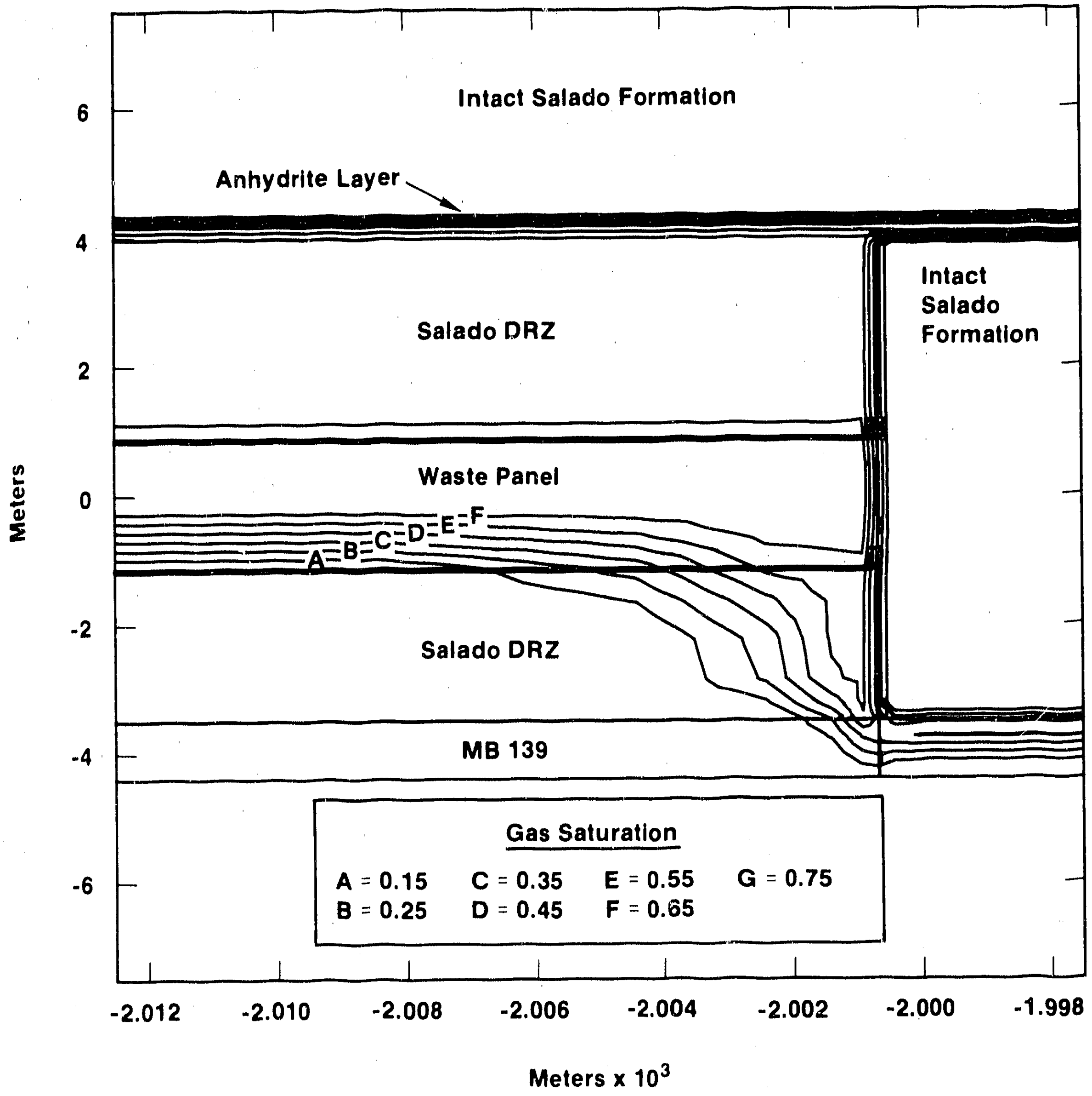
		Permeability				Capillary
Region	Porosity	K_x (m^2)	K_y (m^2)	K_z (m^2)	Compressibility (1/Pa)	Pressure (Pa)
Waste	0.0835	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}	7.54×10^{-11}	0
Intact Salado	0.01	1.0×10^{-21}	1.0×10^{-21}	1.0×10^{-21}	7.54×10^{-11}	1.0×10^{9}
Salado DRZ	0.01	1.0×10^{-21}	1.0×10^{-21}	1.0×10^{-17}	7.54×10^{-11}	0
MB139 DRZ	0.10	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-17}	1.20×10^{-11}	0
Intact MB139	0.01	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-18}	1.20×10^{-11}	0
Anhydrite DRZ	0.10	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-17}	1.20×10^{-11}	0
Intact Anhydrite	0.01	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-18}	1.20×10^{-11}	0

Initial Conditions

	Pressures	Brine Saturation
Waste	101.3 kPa	0.19
Elsewhere	14.9 MPa	1.0

hindering return flow of brine, which must displace gas in MB139 to flow toward the waste.

Because the upper regions of the waste quickly become saturated with gas, initially no brine will flow into an intruding borehole. Brine will flow into the borehole only after brine flowing in from the intact halite and anhydrite has displaced gas sufficiently that brine saturation in the upper part of the waste exceeds the residual brine saturation, assumed to be 20 percent. Brine saturations greater than about 60 percent are required for significant flow into the borehole. The controlling regions predicted by BOAST II are the upper portion of the waste panel, where gas saturation remains highest, and the anhydrite layer, where each phase (gas and brine) remains laterally continuous, thereby permitting flow in each region with minimal hindrance. These predictions justify using a one-dimensional model for preliminary simulations of gas generation and flow when an intruding borehole is present.



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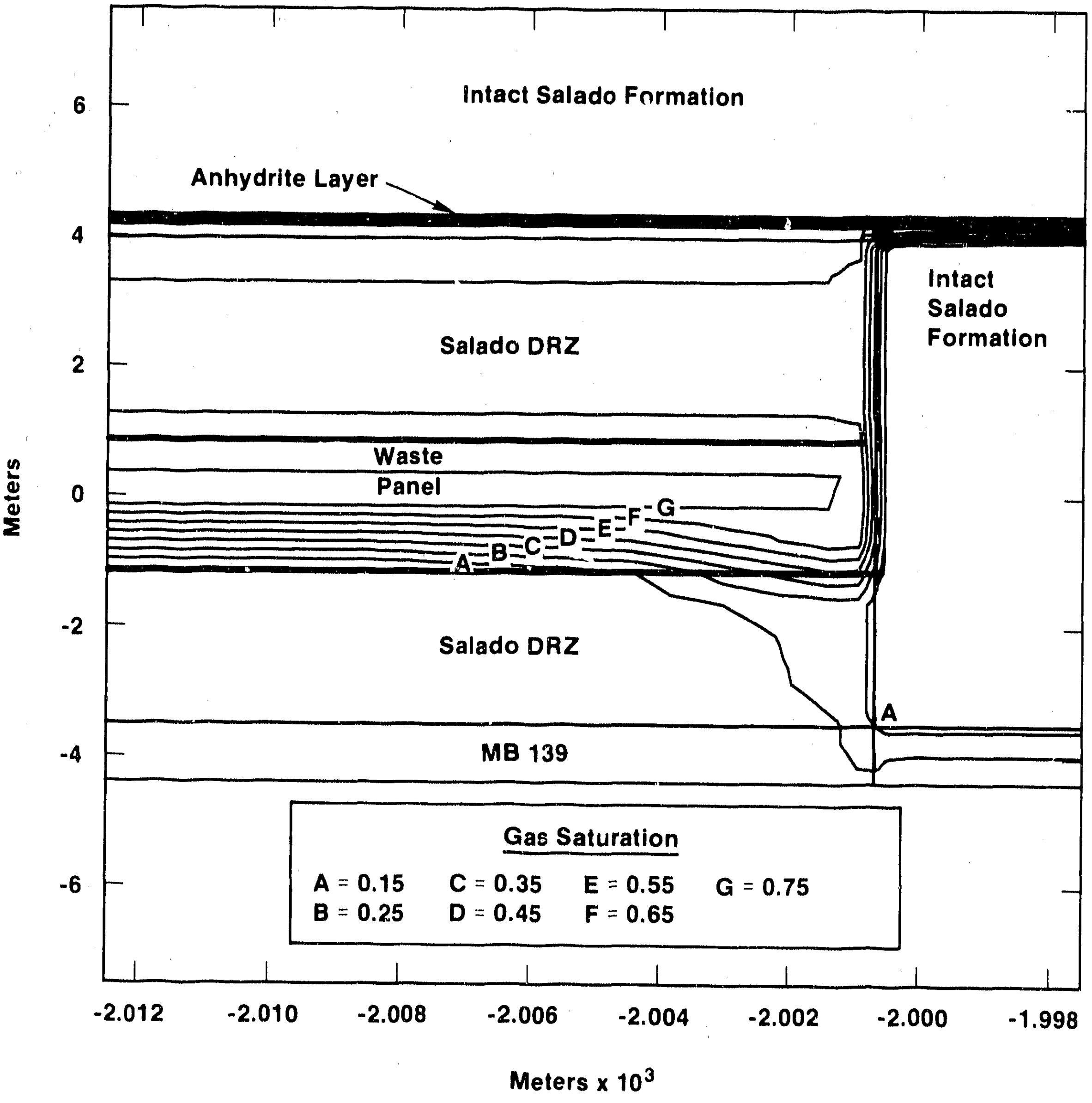
3 Figure VI-9. Gas Saturation Contours at Waste Panel Wall at 713 Years (BOAST II Calculation).



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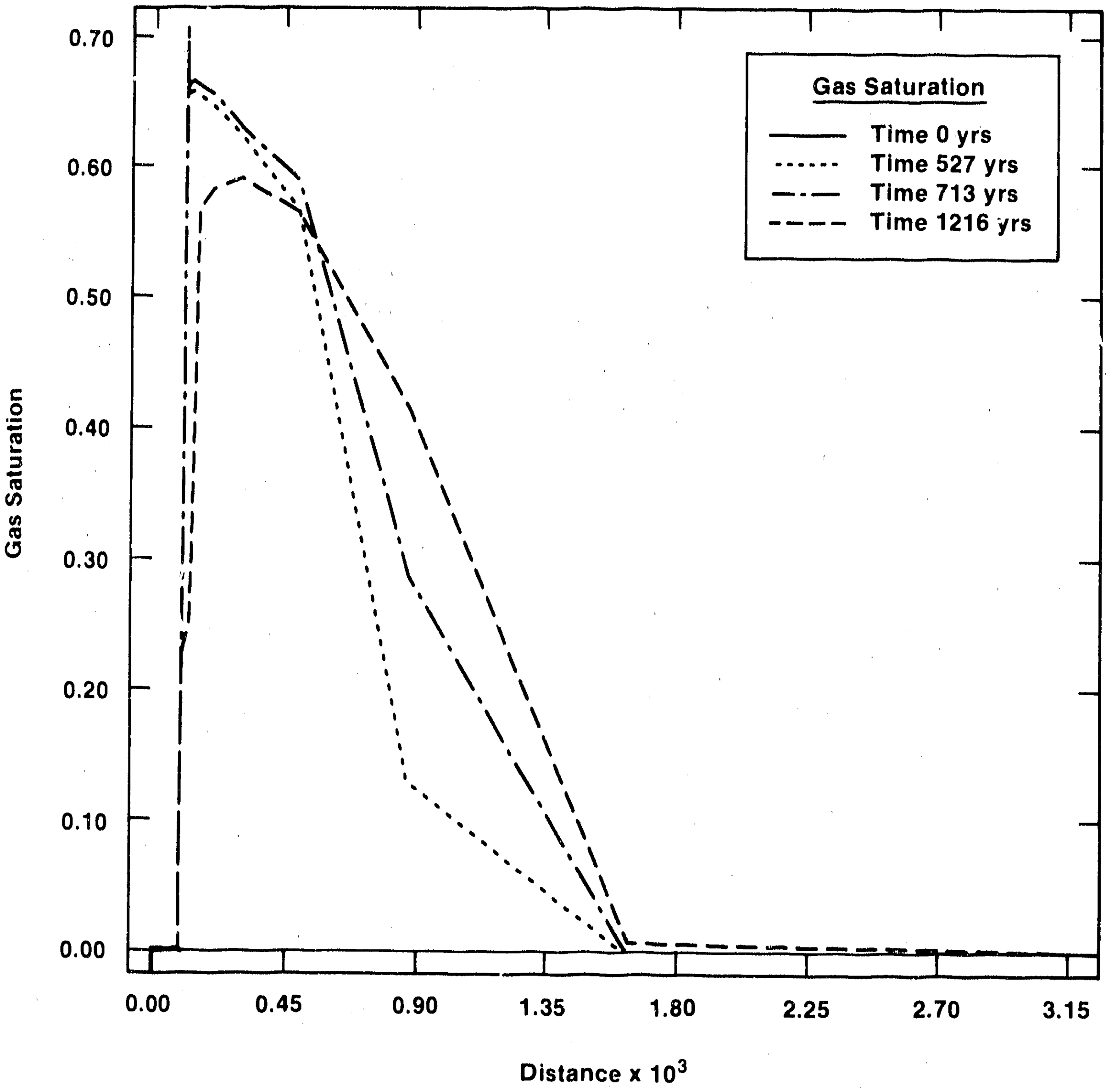
3 Figure VI-10. Gas Saturation Contours at Waste Panel Wall at 1216 years (BOAST II Calculation).



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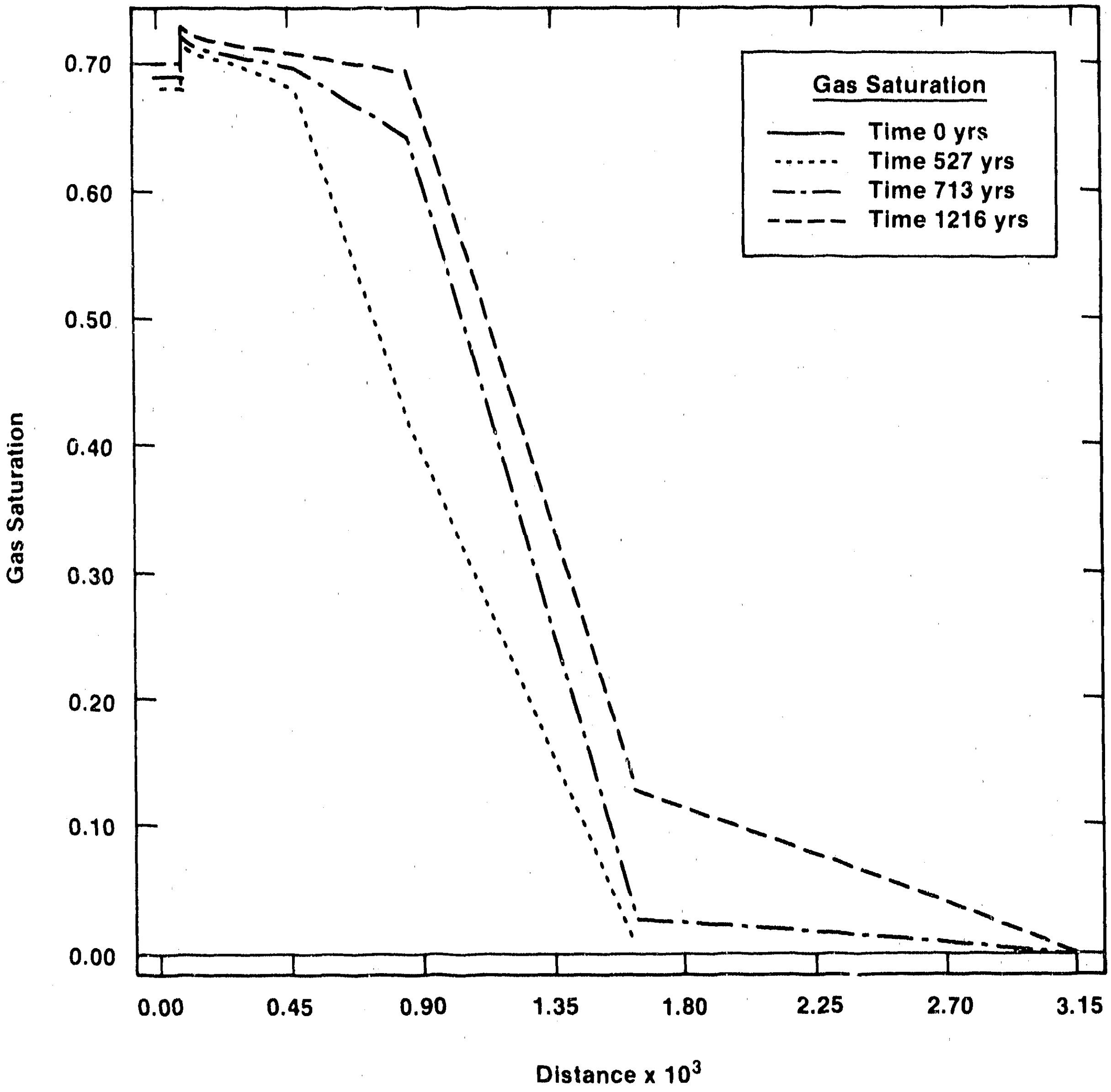
3 Figure VI-11. Gas Saturation Profiles along Top of MB139 (BOAST II Calculation).



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3 Figure VI-12. Gas Saturation Profiles along Top of Combined Anhydrite A and B Layer (BOAST II
4 Calculation).

The BOAST II simulation reflects the selected directional permeabilities. Gas saturation profiles, particularly in the waste, lower DRZ, and MB139, are expected to change with permeability. For example, if large fractures develop in the DRZ, vertical permeability of the lower DRZ could significantly exceed the waste permeability. Brine could be pushed down through the waste and the DRZ and into MB139 more rapidly, resulting in little horizontal variation in gas saturations within the waste or the lower DRZ. Future simulations will examine the effect of a dominant flow path through DRZ fractures to MB139.

When a two-phase model is available within CAMCON, Monte-Carlo simulations will be performed using cdfs for material properties in each region of Figure V-32. For the DRZ above and below the waste, two extremes provide possible bounds for parameter ranges. One bound assumes the fractured halite of the DRZ completely reconsolidates by creep closure before enough gas can be generated to prevent reconsolidation. Material properties for this bound are those of intact halite. The other bound assumes open vertical fractures allow instantaneous gas transport to MB139 and anhydrite layers A and B. The BOAST II and BRAGFLO simulations are closer to the first bound than the second bound. Uncertainty and sensitivity analyses will be included in the 1991 preliminary assessment.

BRAGFLO Simulations

The one-dimensional base case, simulation A, uses material properties shown in Table VI-3. These properties are similar to those used in the two-dimensional BOAST II simulation, except that non-zero capillary pressures were used in all regions. The values of threshold displacement pressure and capillary pressure in the base case are low enough to affect the results little more than zero values. The pressure was fixed in the far right block (Block 31 in Figure VI-8); all other boundaries were no-flow boundaries. Gas-generation rates and durations were the same as in the BOAST II simulation, and were the values reported in Lappin et al. (1989).

Five additional simulations varied anhydrite permeability and capillary pressure and gas-generation rates to examine cumulative brine flow up the intruding borehole (Table VI-4). No other parameters were varied, including gas-generation times or the time of intrusion. The anhydrite permeability of 10^{-18} m^2 (10^{-3} md) used in simulations C through F represents the best estimate of the highest anticipated anhydrite permeability (Rechard et al., 1990b). The capillary threshold pressure of simulation F reflects the highest value reported for the Salado Formation (Rechard et al., 1990b), and is a limiting case. Gas-generation rates were varied between the highest rate anticipated (Lappin et al., 1989) and 0.1 times that value.

TABLE VI-3. MATERIAL PROPERTIES FOR ONE-DIMENSIONAL (BRAGFLO) SIMULATIONS OF GAS-GENERATION EFFECTS ON BRINE FLOW INTO AN INTRUDING BOREHOLE

Region	Porosity	Permeability (m^2)	Capillary Threshold Pressure (Pa)
Waste	0.0835	7.2×10^{-15}	2.02×10^{3}
Salado DRZ	0.03	1.0×10^{-21}	2.02×10^{3}
Intact Anhydrite	0.0055	1.0×10^{-18}	3.00×10^{5}

Initial Conditions

	Pressures	Brine Saturation
Waste	101.3 kPa	0.19
Elsewhere	~16.0 MPa	1.0

TABLE VI-4. PARAMETERS VARIED FOR SIX ONE-DIMENSIONAL SIMULATIONS OF GAS-GENERATION EFFECTS ON BRINE FLOW INTO AN INTRUDING BOREHOLE

Simulation	Permeability[a] m^2	Gas Generation Rate[b] Moles/Drum/Year	Threshold Pressure MPa
A	1.0×10^{-19}	1.7/0.85	0.3
B	1.0×10^{-19}	0.85/0.425	0.3
C	1.0×10^{-18}	1.7/0.85	0.3
D	1.0×10^{-18}	0.85/0.425	0.3
E	1.0×10^{-18}	0.17/0.085	0.3
F	1.0×10^{-18}	1.7/0.85	23.0

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[a] For intact anhydrite

[b] Anoxic Corrosion/Biogas

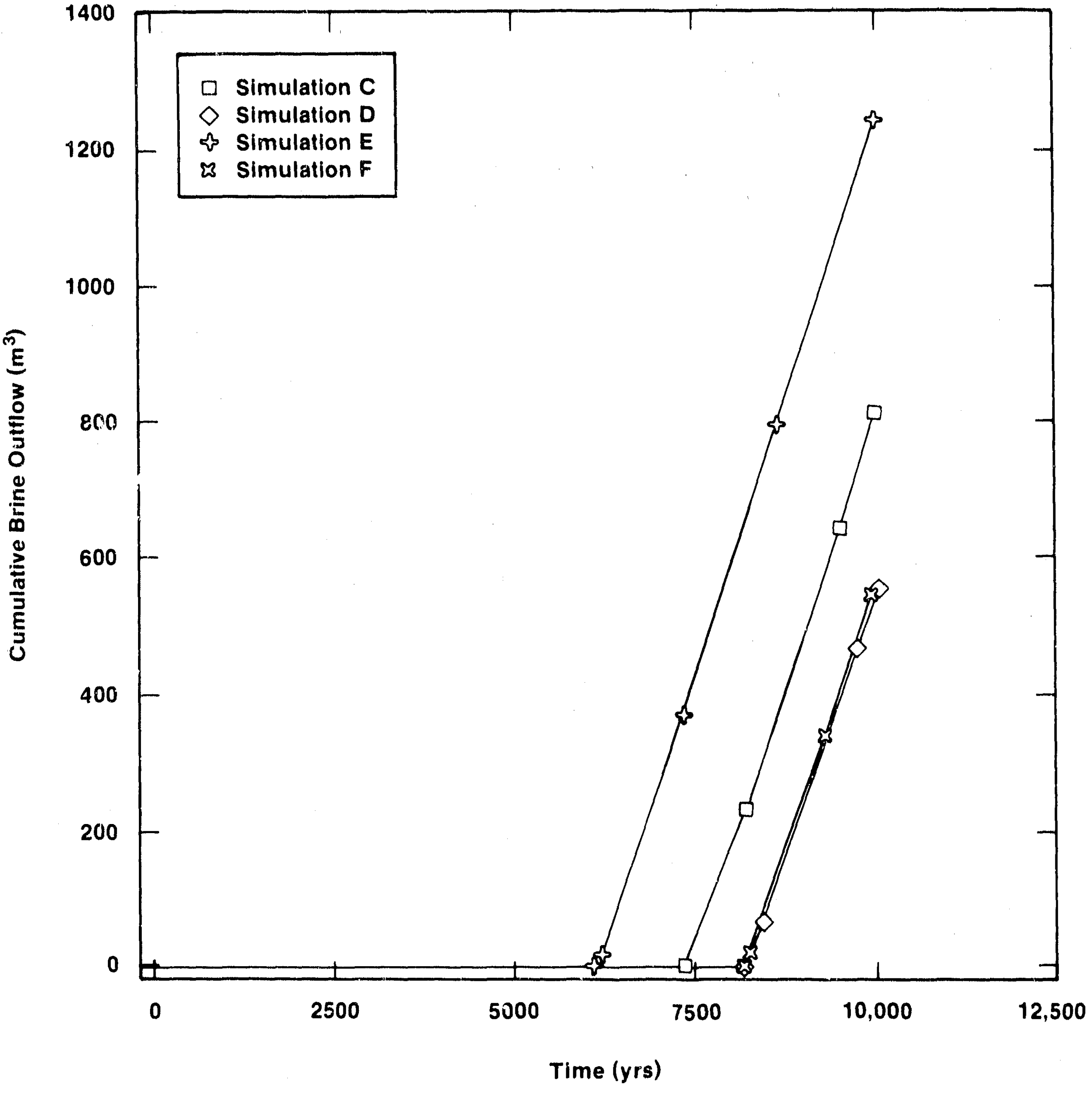
Conclusions are based on one-dimensional simulations; extrapolation to two-dimensional geometry should not be inferred. The results (Figure VI-13) indicate that brine flows into an intruding borehole only at the upper limit of anhydrite permeability (10^{-18} m^2) (10^{-3} md). Neither simulation A nor B showed brine outflow into the borehole (Table VI-5). The brine front after intrusion only penetrates the far boundary of the waste panel in either case at 10,000 years.

At the upper limit of anhydrite permeability, brine flow into the borehole depends on gas-generation rate (i.e., total gas generation). The brine outflow is greater at both the maximum generation rate (simulation C) and at one tenth of the maximum generation rate (simulation E) than at one half of the maximum rate (simulation D). This apparent minimum in brine outflow reflects the relative importance of at least two phenomena: the degree to which gas pressure forces brine out into the anhydrite away from the panels prior to intrusion (Table VI-5, column 3); and the pressure driving brine toward the borehole after intrusion (Table VI-5, column 5). For the high gas-generation rate (simulation C), brine is forced farther away from the panel, but the pressure drive toward the borehole is greater than at one half of the maximum generation rate (simulation D). For low gas-generation rate (simulation E), brine is not forced out of the panel as far, and the pressure drive toward the intrusion borehole exceeds that at one-half the generation rate (simulation D) as well as at the maximum generation rate (simulation C).

Simulation F evaluated the dependence of brine outflow on capillary threshold pressure. The simulation is an artificially limiting case, because the threshold pressure was elevated independently of the permeability of the media. The high capillary threshold pressure corresponds to a permeability of 10^{-22} m^2 (10^{-7} md). No brine outflow would be expected at this low, far-field permeability for the intact Salado Formation, and permeability was instead arbitrarily held at the maximum value of 10^{-18} m^2 (10^{-3} md), allowing brine to flow. Results of this simulation indicate that raising capillary pressure inhibits the flow of brine not only out of the panel during gas generation (even though panel pressures are increased), but also toward the borehole after intrusion because of the lower brine pressure. Comparison of simulations F and C indicates that with other parameters equal, an increase in capillary threshold pressure reduces cumulative brine flow into the borehole.

CONCLUSIONS FROM PRELIMINARY SIMULATIONS INCLUDING GAS GENERATION

Two-dimensional, two-phase flow simulations using BOAST II suggest that in the undisturbed state, gas saturation will be high in the upper portion of the waste, MB139, and the overlying anhydrite layer. Gas migration in MB139 and the combined anhydrite layers A and B may occur over as much as 3 km



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3 Figure VI-13. Cumulative Brine Flow into an Intruding Borehole (BRAGFLO Calculation).

TABLE VI-5. RESULTS OF SIX ONE-DIMENSIONAL SIMULATIONS OF GAS-GENERATION EFFECTS ON BRINE FLOW INTO AN INTRUDING BOREHOLE

Simulation	I Break Through[a] (yrs)	II Brine Flow[b] (m^3)	III Gas[c] Penetration	IV Flow Reversal[d] Time (yrs)	V Pressure Drive[e] (psi)
A	$>1.0 \times 10^4$	0	25/.10	1.30×10^3	252.0
B	$>1.0 \times 10^4$	0	13/.16	1.24×10^3	149.0
C	7.3×10^3	802.0	28/.17	2.10×10^3	260.0
D	8.2×10^3	550.0	27/.06	1.33×10^3	169.0
E	6.0×10^3	1235.0	11/.81	1.18×10^3	792.0
F	8.2×10^3	544.0	28/.01	1.36×10^3	240.0

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[a] Time brine starts flowing through borehole

[b] Total brine flow out borehole

[c] Grid block/gas saturation; penetration due to gas drive prior to intrusion

[d] Time brine begins to flow back to waste from intact anhydrite after intrusion

[e] Brine pressure driving force (domain boundary to brine front) after intrusion

(2 mi). One-dimensional, two-phase flow simulations using BRAGFLO indicate that factors controlling brine flow to an intruding borehole include the gas-generation rate, anhydrite permeability, and anhydrite capillary pressure.

As simulated, brine will flow into an intruding borehole if the anhydrite permeability is at its maximum of 10^{-18} m^2 (10^{-3} md). No brine will reach the borehole within 10,000 years if anhydrite permeability is 10^{-19} m^2 (10^{-4} md) or lower.

At maximum anhydrite permeability, simulated brine flow into the borehole depends on gas-generation rate and capillary pressure. Comparison of simulations with different gas-generation rates suggests that brine flow into a borehole could reach a minimum value for gas-generation rates between the maximum and one tenth of the maximum.

GOALS FOR FUTURE TWO-PHASE FLOW SIMULATIONS

Results presented here for gas generation are preliminary, and are primarily a demonstration of the methodology that will be further developed to assess the effects of gas generation on repository performance. More detailed analyses, requiring two-dimensional modeling of two-phase flow following intrusion, will be conducted after the two-dimensional version of BRAGFLO is verified. Conceptual models and data must also be developed to describe adequately the coupled processes of gas-generation, brine saturation, and salt creep. For the simulations presented in the preceding sections, gas-generation rates were assumed to be independent of brine saturation. As discussed qualitatively in Chapter V ("Waste Panel Modeling"), gas generation consumes water, and rates will drop as gas displaces brine from the waste. Simulations also assumed that permeability of the anhydrite remains constant, rather than a function of gas pressure that opens pre-existing fractures as gas migrates away from the waste panels. Two-dimensional BRAGFLO simulations will include these two important factors. The importance of other modeling issues (Table V-7) will be assessed through sensitivity analyses.

VII. INDIVIDUAL PROTECTION REQUIREMENTS

The text of Chapter VII is preceded by a synopsis that simplifies concepts presented in Chapter VII. Detailed information about those concepts is in the text following the synopsis.

Synopsis

The Individual Protection Requirements set limits on the amount of radiation that is acceptable for members of the public in the accessible environment for 1,000 years after disposal.

A recent study indicates that, in the absence of human intrusion, releases via a route through the Culebra Dolomite Member of the Rustler Formation to a livestock well will not occur in the 1,000-year time scale because no radionuclides will escape from the undisturbed repository.

Additional preliminary doses will not be calculated unless a revised Subpart B makes them necessary.

Dose Considerations	For undisturbed conditions, radionuclides did not migrate out of the repository/shaft system even when the simulations were extended to 50,000 years, well beyond the 1,000 years required by the Standard. Additional disposal-system characterization, including gas generation, is not expected to produce data that will significantly alter the no-release results.

The Standard contains Individual Protection Requirements:

> Disposal systems for transuranic wastes shall be designed to provide a reasonable expectation that for 1000 years after disposal, undisturbed performance of the disposal system shall not cause the annual dose equivalent from the disposal system to any member of the public in the accessible environment to exceed 25 mrem to the whole body and 75 mrem to any critical organ. (§ 191.15)

Two previous studies (U.S. DOE, 1980a; Lappin et al., 1989) reported doses to humans resulting from hypothetical releases from WIPP for selected scenarios. Although these studies employed deterministic calculations and were not concerned with assessing compliance with § 191.15, they have an important bearing on the design of probability-based dose calculations. The approach in the *WIPP Final Environmental Impact Statement* (U.S. DOE, 1980a) for analyzing the effects of radioactivity released from the WIPP was to estimate the consequences of five different hypothetical scenarios that might move radionuclides to the biosphere. The analyses of these scenarios proceeded from radionuclide movement through the geosphere to transport through the biosphere after discharge into the Pecos River at Malaga Bend, and finally, predicted radiation doses received by people. The human dose estimates were based on the *Report of ICRP Committee II on Permissible Dose for Internal Radiation, International Commission on Radiological Protection, Publication 2* (ICRP, 1959), usually referred to as ICRP 2. The travel times for radionuclides arriving at Malaga Bend were on the order of a million years, but this study predates the Standard, which specifies a time scale of one thousand years for individual protection.

The second study (Lappin et al., 1989) analyzed the effects of release of radioactivity from the WIPP by estimating the consequences of two different hypothetical cases. Human dose estimates were based on the new ICRP philosophy as described in ICRP Publications 26 (ICRP, 1977) and ICRP 30 (ICRP, 1979).

The Standard requires that an uncertainty analysis of undisturbed conditions be performed to assess compliance with § 191.15. In this case, the performance measure is dose to humans. However, a recent study (Lappin et al., 1989) indicated that, in the absence of human intrusion, releases resulting in doses via a route through the Culebra Dolomite Member to a livestock well will not occur in the 1000-year time scale of § 191.15. Repeating that study to include uncertainty analyses is unlikely to provide any sample of parameter values from current distributions that would result in doses in a 1000-year time scale. Evaluations of undisturbed performance by Marietta et al. (1989), results of which are repeated in the following section, indicate that radionuclides will not migrate out of the repository/ shaft system during 1000 years. Therefore, dose calculations are not expected to be a part of the WIPP assessment of compliance with *40 CFR Part 191*. However, Subpart B is in remand. The outcome of the remand could require dose calculations over longer times. This discussion presents the WIPP performance assessment approach for calculating human doses if required.

Calculations have not been updated in 1990, and the results summarized here are those presented in the methodology demonstration (Marietta et al., 1989).

Undisturbed performance is simulated using the base case scenario as described in Chapter III. Dose analyses for purposes other than comparison to § 191.15 also can be performed using this methodology.

Repository/Shaft System Overview for the Demonstration

Three evaluations of undisturbed performance are reported here. These are (1) one simulation, referred to as IA, using reference (best-estimate) parameter values (Appendix B in Marietta et al., 1989); (2) one simulation, IB, using parameter values degraded from the best estimate (Appendix B in Marietta et al., 1989); and (3) fifty simulations using Latin-hypercube-sampled values for uncertainty analysis of the parameters (Marietta et al., 1989).

Uncertainty analysis of undisturbed performance was based on probability density functions representing the most realistic estimates of minimum, maximum, and expected or median values and distributions of parameters (Appendix C in Marietta et al., 1989). Monte Carlo samples of each parameter's pdf were used for 50 simulations of system performance (Marietta et al., 1989).

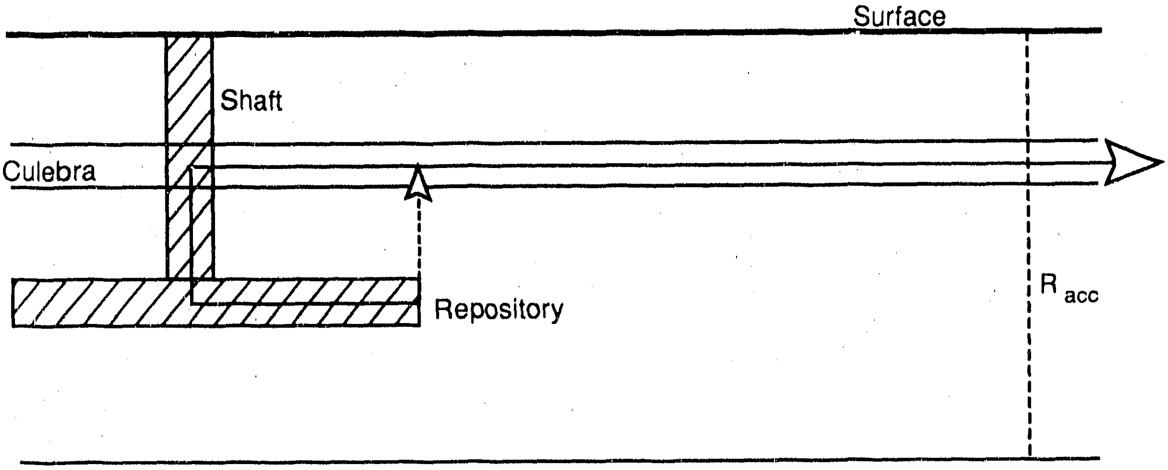
In these simulations, no radionuclides move out of the repository/shaft system during 1000 years of regulatory concern. Because of this slow rate of radionuclide movement, simulations were extended to 50,000 years to assess system performance. Even at this longer time interval, no radionuclides travel as far as the middle of the shaft-seal system. As a result, the following discussion considers radionuclide migration to the base of the shaft and through the MB139 seal below the repository (Marietta et al., 1989).

For the purposes of the methodology demonstration, the repository was assumed to be consolidated, and all legs in the network along the flow path are assumed to be saturated from the time of repository decommissioning. This conservative assumption results in radionuclide migration throughout the 50,000 years simulated (Marietta et al., 1989). Panels were assumed filled with waste and backfill and no free water was present. MB139 is fractured as a result of excavation of the drifts and panels, and in response to later salt creep into these excavations. These new fractures occur directly under all excavations, but not under the intact salt pillars. Grout seals are in place in MB139 directly under panel seals. All access drifts and the experimental area are backfilled, and the shafts are sealed (Lappin et al., 1989).

The effects of gas generation were not considered in the methodology demonstration. However, gas generation has been considered by Lappin et al. (1989). They determined that microbiological degradation of organic material in waste containers begins when the containers are filled and continues in the repository. As salt creep closes rooms and drifts, waste containers rupture, and gas enters voids in the rooms and drifts. Gas migrates into MB139 through the marker bed seals and eventually fills the fracture volume. Gas pressure rises, slowing room closure and brine inflow, and maintaining open fractures in MB139. As gas generation slows, brine begins to resaturate the repository and MB139. The balance of creep closure, gas generation and dispersion, and resaturation with host rock brines is complex and highly dependent on room chemistry and waste types. If the waste panels are partially or fully saturated, transport can occur by advection in pressure-driven brine, provided a pressure gradient exists, and by diffusion (Lappin et al., 1989).

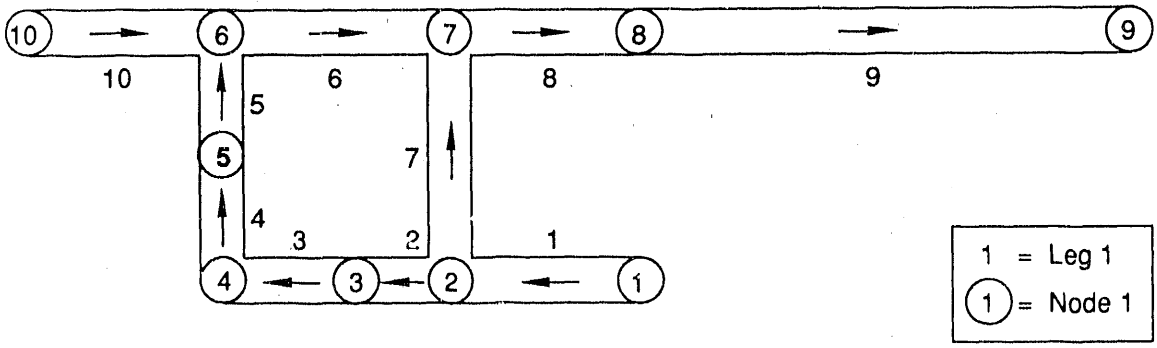
NEFTRAN was used to simulate steady-state groundwater flow and radionuclide transport under saturated conditions by subdividing the flow field into a network of one-dimensional "legs." Darcy flow was assumed for all porous materials along the flow path. Mass was conserved at each junction. These legs may be configured to represent multidimensional flow fields. Radionuclide transport was simulated using a distributed velocity method in which an average velocity was calculated for each isotope from the isotopic velocities in all the legs along the flow path. A generalized flow network (Figure VII-1) for NEFTRAN simulations of undisturbed performance indicates assumed flow direction (arrows) along each leg (uncircled numbers) and nodes (circled numbers) (Marietta et al., 1989).

The relationship between legs in the network and the conceptual model is as follows: Leg 2 represents the seal in MB139; Leg 3 represents MB139 between the seal and base of the shaft; Leg 4 represents the lower, well-consolidated waste-shaft seal (the largest of the four shafts); Leg 5 represents the upper, less well-consolidated shaft seal; Legs 6, 8, and 9 represent the Culebra Dolomite; and Leg 7 represents the intact Salado Formation between the repository and Culebra Dolomite. Leg 1 represents the repository and is included to establish flow toward the seal in MB139, and Leg 10 represents existing flow through the Culebra Dolomite Member. A stock well into the Culebra Dolomite is represented by Node 9. Options in this computer program treat the Culebra Dolomite as either a single- or a dual-porosity medium. Because undisturbed performance of the disposal system prevents migration of radionuclides to the Culebra Dolomite Member within 10,000 years, flow in the Culebra Dolomite Member was not simulated (Lappin et al., 1989; Marietta et al., 1989).



Conceptual Model

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



Flow Network

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Figure VII-1. Simplified Conceptual Model and Network for the Undisturbed Disposal System (Marietta et al., 1989; after Lappin et al., 1989).

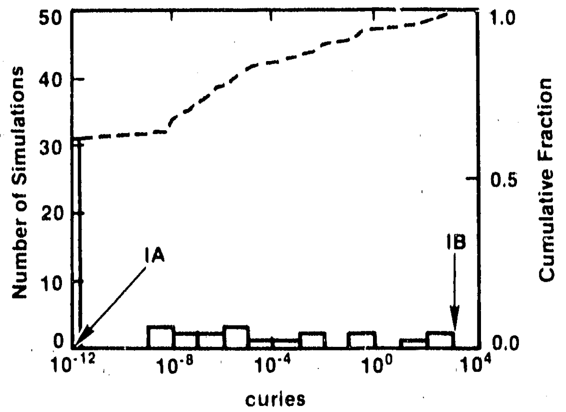
Radionuclide-transport calculations included pathways through Legs 1, 2, 3, 4, 5, 6, 8, and 9, and through Legs 7, 8, and 9. Because NEFTRAN integrates nuclide arrivals at a particular node and not at intermediate nodes, and arrival times to certain nodes along the path through MB139 and the shaft are extremely long, separate simulations were required to determine migration through the shaft to the Culebra Dolomite (Node 6), to the junction of the upper and lower shaft seals (Node 5), to the base of the shaft (Node 4), and to the end of the MB139 seal (Node 3). For the path directly from the repository to the Culebra Dolomite, separate simulations were required to estimate radionuclide migration to Node 7 (Lappin et al., 1989; Marietta et al., 1989).

The flow network is driven by the pressure gradient between the waste panels (Node 1) and the Culebra Dolomite Member (Node 6). Node 1 pressure was assumed conservatively to be lithostatic (14.8 MPa); the Node 6 pressure was set at 1.0 MPa. Pressure was not sampled during the Monte Carlo analysis. The entire system was assumed to be saturated, and one-dimensional Darcy flow was calculated along each leg. Transport of radionuclides was calculated to each node along the pathway to the Culebra (Marietta et al., 1989).

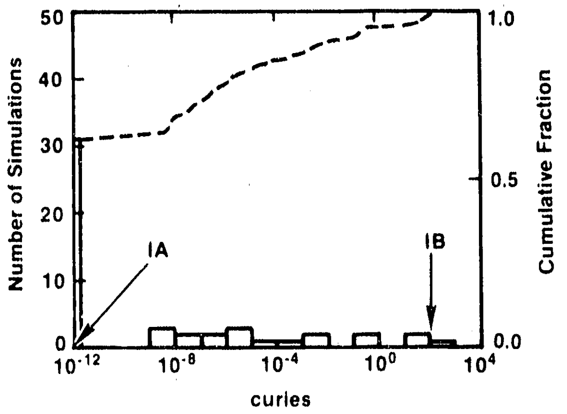
Results

Of the 12 radionuclides tracked for the methodology demonstration, uranium-233, uranium-234, and thorium-229, in decreasing order, dominated migration to the base of the shaft (NEFTRAN Node 4 in Figure VII-1), based on the average curies per radionuclide for the 50 simulations. For each radionuclide, the distribution appeared exponential, although only 19 simulations resulted in more than 1×10^{-10} Ci arriving at the base of the shaft (Figure VII-2). The results for these simulations varied over ranges of 11 to 13 orders of magnitude depending on the radionuclide, indicating that the sampled parameter values had a profound effect. For some parameters, the values for degraded conditions (IB) were not an end-point value of the parameter's range. For example, migration through degraded seals (IB) was less than migration for some of the 50 simulations in the uncertainty analysis (Table 4-1 in Marietta et al., 1989). Degraded parameter values were not always the least-favorable choice, therefore, and outlying (low-probability) sampled values could result in greater migration of radionuclides (Figure VII-2) (Marietta et al., 1989).

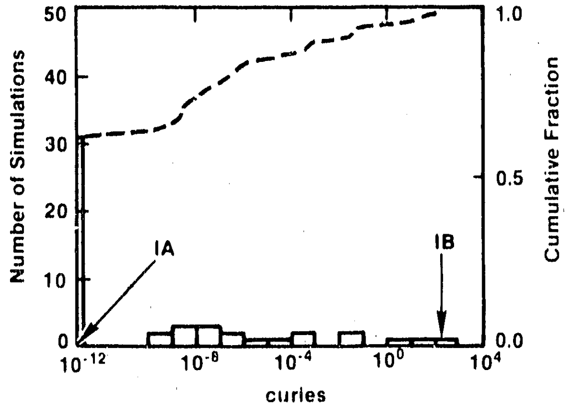
The dominant radionuclides migrating through the MB139 seal (NEFTRAN Node 3 in Figure VII-1) were, in decreasing order, plutonium-239, plutonium-240, thorium-229, and americium-241 (Figure VII-3; Table 4-2 in Marietta et al., 1989). The nonuniform distributions resulted from the relatively large



a. Uranium-233



b. Uranium-234



c. Thorium-229

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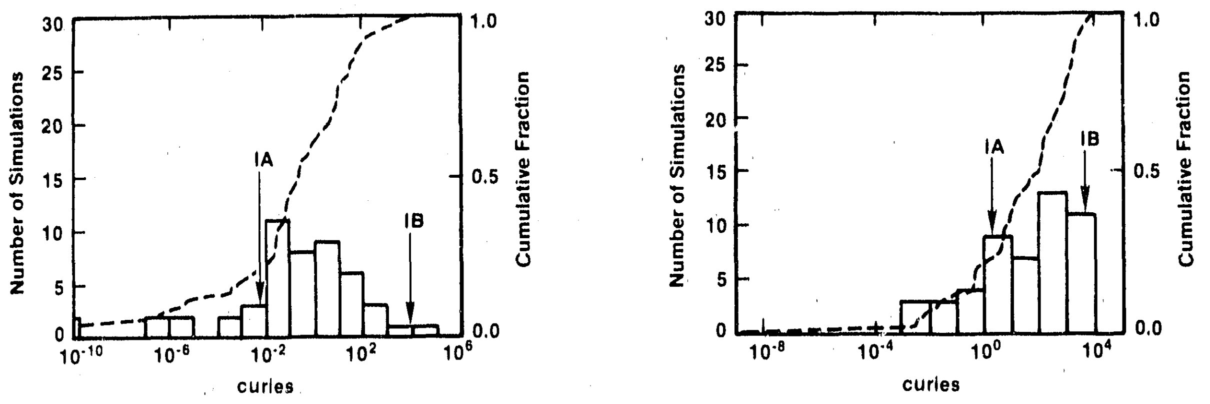
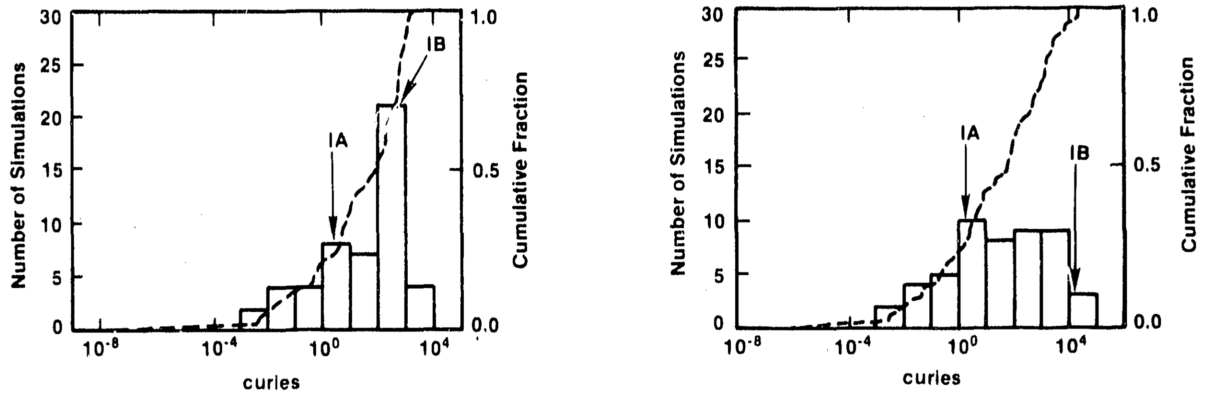
Figure VII-2. Histograms of Frequency of Simulations in which Quantities of Radioisotopes Migrate to the Base of the Shaft in 50,000 yr, Showing the Cumulative Fractional Density of Simulations, for Undisturbed Performance. 1A and 1B indicate values calculated assuming reference and degraded parameter values, respectively (Marietta et al., 1989).



a. Plutonium-239

b. Plutonium-240



c. Thorium-229

d. Americium-241

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Figure VII-3. Histograms of Frequency of Simulations in which Quantities of Radioisotopes Migrate through the MB139 Seal in 50,000 yr, Showing the Cumulative Fractional Density of Simulations, for Undisturbed Performance. 1A and 1B indicate values calculated assuming reference and degraded parameter values, respectively (Marietta et al., 1989).

frequency for migration of certain quantities of each radionuclide. Whereas the quantities tended to be in the same range to only slightly larger than at the base of the shaft, the frequencies were much greater (Marietta et al., 1989).

The demonstration analysis for undisturbed conditions indicated no releases from the repository in either the 1000-year period for Individual Protection Requirements (§ 191.15) or the 10,000-year period for Containment Requirements (§ 191.13). In lieu of releases, transport through the MB139 seal and through MB139 to the bottom of the lower shaft seal was evaluated. The fact that no releases occurred indicates that no dose calculations are needed for demonstrating compliance with Individual Protection Requirements. Furthermore, this long-term isolation under undisturbed conditions confirms the project's early choices of repository design and location for an essentially gas-free repository. The effect of gas on long-term performance is yet to be determined, but is not expected to change this conclusion (Marietta et al., 1989).

Two-dimensional, two-phase flow simulations using idealized room geometry and local stratigraphy corroborate this expectation (see Chapter VI, "Preliminary Simulations Incorporating Gas Generation"). Such simulations of undisturbed performance assume panel seals that consolidate to intact halite properties in the drift, but no seal in either MB139 or the anhydrite layers A and B. Figures VI-11 and VI-12 show gas saturation in MB139 and the overlying anhydrite layers versus distance for the highest postulated gas generation rate of 2 moles/drum/year. As calculated, gas migration away from the room occurs over a length scale longer than the drift length from the northernmost panel seal to the closest shaft, and the shaft/drift interfaces are located in the peak gas saturation portion of those curves, where transport of dissolved radionuclides, which requires a liquid medium, is diminished. In addition, brine content in the waste is diminished due to the presence of gas, so less brine is available to transport radionuclides, and very little gas or brine has moved into the lower permeability, intact halite surrounding the fractured anhydrite and the DRZ. The gas-generation rate is a function of brine saturation in the waste (anoxic corrosion requires water), so residual brine in the waste is consumed, further diminishing the radionuclide transport potential. Therefore, for undisturbed performance, the brine-saturated case is believed to bound the two-phase case for radionuclide transport upward through the shaft. This hypothesis will be tested further in the 1991 performance assessment.

VIII. ASSURANCE REQUIREMENTS PLAN

The text of Chapter VIII is preceded by a synopsis that simplifies concepts presented in Chapter VIII. Detailed information about those concepts is in the text following the synopsis.

Synopsis

The WIPP Project has prepared a preliminary plan for implementing the Assurance Requirements of the 1985 Standard.

Active Institutional Controls

The objectives of active institutional controls at the WIPP are to

Restore the land surface to its original condition to avoid future preferential selection of the area for incompatible uses.

Provide a facility and presence at the site during active cleanup.

Monitor the disposal system.

Disposal System Monitoring

The objective of a monitoring program would be to detect substantial and detrimental deviation from the expected performance of the disposal system.

Numerous subsidence monuments have been installed to monitor subsidence and diagnose unexpected change in the disposal system.

Passive Institutional Controls

The objectives of passive institutional controls at the WIPP are to deter human intrusion into the repository and to minimize inadvertent intrusion, as outlined in Appendix B to the Standard.

Passive institutional controls include

- Markers warning of the presence of buried nuclear waste and identifying the boundary of the controlled area.
- External records about the WIPP repository.
- Federal ownership.

Passive Markers

Appendix B of the Standard assumes that

- Inadvertent human intrusion into the repository can be mitigated by a number of approaches, including the use of passive controls such as markers.
- The effects of passive institutional controls such as markers will be estimated.

Expert Judgment

The expert-judgment approach uses teams of experts representing various fields that are pertinent to the issue.

The experts provide a broad perspective on the problem and identify outcomes that often can be expressed as numerical data for computer models.

Future Intrusion

Experts provide

- Hypotheses on how future societies may inadvertently intrude the repository.
- Insights on the ability of future societies to interpret and heed warnings about nuclear waste buried at the WIPP.
- Probabilities of the various foreseeable futures (possible future states of society that can be imagined now) and of the extent these foreseeable futures account for the state of society.

For each foreseeable future, the experts will

- Identify and quantify expected modes of intrusion into the repository.

> Address issues relating to persistence of information about the WIPP, the ability to detect radiological waste in the repository, and the existence of radiological waste in the repository.

Futures can be constructed by considering alternative projections of basic trends in society.

Each future specifies the potential characteristics of society at various points in the future.

From the states of societies and their potentially intrusive activities, modes of intrusion and motivations for these intrusions can be inferred.

Marker Development

Experts

> Develop the characteristics of a marker system to warn future societies of the presence of nuclear waste in the WIPP repository.
>
> Assess the effectiveness of such a marker system.

The marker-development experts will

> Define characteristics for selecting and manufacturing markers to be placed at the WIPP.
>
> Estimate the performance of these markers over the 10,000 years following installation.

Results of Expert Judgment

The future-intrusion experts will provide a written report discussing societal development and possible futures, as well as the basis for estimating the possibilities of these futures.

Quantitative (probabilistic) estimates of the frequencies of various intrusions will be developed.

The intrusion modes identified by the future-intrusion experts will help guide the marker-development group.

Marker-development experts will estimate the effectiveness of various types of markers in deterring human intrusion over the 10,000 years of regulatory concern.

The results of both groups will be summarized and conveyed to the DOE and the WIPP performance-assessment team.

Federal Ownership of the WIPP

The DOE or a successor government agency will own and control the land and institute regulations that restrict land use and development, as required by the Standard.

Records of the WIPP

Records will be preserved of the disposal site and its contents.

Records will warn about the potential effects of drilling through the repository and specify techniques for borehole plugging, should exploratory drilling cause an intrusion.

Multiple Barriers

The Standard requires that both natural and man-made barriers be used as part of the isolation system.

At the WIPP, natural barriers include

The salt formation.
The geohydrologic setting.

Man-made barriers include

Backfills.
Plugs and seals that isolate volumes of wastes.

The effectiveness of these barriers is being modeled for the performance assessment.

Natural Resources	The WIPP Project has met the requirement that the favorable characteristics of the location outweigh the possibility of the repository being disturbed in the future.
Waste Removal	The Standard requires that it be possible to locate and recover the waste for a reasonable period of time after disposal. The EPA has stated that current plans for mined geologic repositories meet this requirement without additional design.

As prescribed in the Second Modification to the Consultation and Cooperation Agreement, the WIPP Project has prepared a plan for implementing the Assurance Requirements of the 1985 Standard (U.S. DOE, 1987a). The plan is preliminary, because methods and technologies could evolve over the operational time period. In accordance with the Project's interpretation of the EPA's intention, the Project will select assurance measures based on the uncertainties in the final performance assessment. This chapter will be updated as the management and operating contractor (see Chapter I) updates the implementation plans. The current plan includes definitions and clarifications of the Standard as it applies to the WIPP, the implementation objective for each requirement, an outline of the implementation steps for each requirement, and a schedule of activities leading to final compliance. This chapter summarizes plans for implementing the Assurance Requirements.

Active Institutional Controls

Active institutional controls are expected to include post-operational monitoring, decontamination and decommissioning, land reclamation, evaluation of land use in the area, maintaining fences and buildings, and guarding the facility. The objectives of these activities are to restore the land surface to its original condition to avoid future preferential selection of the area for incompatible uses, to provide a facility and presence at the site during active cleanup, and to monitor the disposal system.

All performance-assessment calculations begin 100 years after the WIPP is decommissioned, thus assuming that active control is maintained for 100 years.

Disposal System Monitoring

Monitoring is required until there are no significant concerns to be addressed by further monitoring. The objective of a monitoring program would be "to detect substantial and detrimental deviation from the expected performance of the disposal system" (§ 191.14(b)). Monitoring activities will be identified during the course of the performance assessment. Numerous subsidence monuments have been installed to monitor subsidence as an indicator of unexpected changes in the disposal system.

Passive Institutional Controls

The Project will implement passive institutional controls over the entire controlled area of the WIPP. Passive institutional controls include markers warning of the presence of buried nuclear waste and identifying the boundary of the controlled area, external records about the WIPP repository, and continued federal ownership. The EPA assumes in the Guidance to the Standard that passive institutional controls will reduce the possibility of inadvertent human intrusion into the repository. Compliance evaluation for the Standard must include the potential for human intrusion and the effectiveness of passive institutional controls to deter such intrusion. The remainder of this section discusses development of three types of passive institutional controls.

PASSIVE MARKERS

According to guidance in Appendix B of the Standard, inadvertent human intrusion can be mitigated by a number of approaches, including the use of passive controls such as markers. The guidance also suggests that the effects of passive institutional controls such as markers should be estimated.

Identifying possible modes of intrusion and projecting what kind of markers would adequately deter such intrusions are at best qualitative tasks. Because the Standard allows for exceptions to quantitative evaluations where qualitative judgments are the only choice and because the expertise to make the qualitative evaluations is not available within the Project, the Project has selected teams of outside experts to address possible modes of inadvertent intrusion and types of markers to deter intrusion. These experts are evaluating the available information, reducing the problems to manageable components, and, with the assistance of probability specialists, quantifying their subjective conclusions to the greatest extent possible. The events and probabilities generated by these experts will be evaluated for incorporation into the performance assessment.

Principles of Expert-Judgment Elicitation

Expert-judgment elicitation is often used to address technical issues that cannot be practically resolved by other means (Bonano et al., 1989; Hora and Iman, 1989). Teams of experts represent the various fields that are pertinent to the issue at hand. The experts not only provide a broad perspective on the problem, but the outcome of their work can often be expressed in numerical form (events probabilities) that can be incorporated into computer models. Before beginning their task, the experts are provided necessary background information and an explicit statement of the issue(s) to be addressed.

Training the experts to synthesize their expertise into relatively unbiased probabilities is fundamental. A common method of addressing such questions is to "decompose" each question into constituent parts that can be readily quantified. Expert interaction and the sharing of insights enhances decomposition and analysis of the questions. Individuals knowledgeable in both the topic under discussion and expert elicitation quantify the responses from each expert.

Planned Expert-Judgment Elicitation

Two expert-judgment elicitations are underway to develop a passive marker system for the WIPP:

Future Intrusion. An expert panel has convened and is now examining how future societies could inadvertently intrude into the repository and what ability future societies will have to interpret and heed warnings about radioactive waste buried at the WIPP.

Marker Development. An expert panel will convene to develop characteristics for and assess the effectiveness of markers to warn future societies of the WIPP repository.

The possible modes of intrusion and projected effectiveness of warnings identified by the future-intrusion experts will be provided to the marker-development experts as the starting point for marker development. Also, a third expert panel to evaluate physical barriers against inadvertent human intrusion is planned. Future-intrusion and marker-development activities are discussed here.

The future-intrusion experts have been asked to address issues related to societal development and human activities that could lead to inadvertent human intrusion in a time frame that extends 10,000 years after disposal. They were asked to identify reasonable, foreseeable futures for human societies and suggest how the activities of these societies could result in intrusions into the WIPP repository and to provide probabilities of the various futures and the degree of completeness that these foreseeable futures represent (to what extent can what could happen to society be accounted for by these foreseeable futures). For each foreseeable future, the experts will be asked to identify and quantify expected modes of intrusion into the repository and to examine issues relating to persistence of information about WIPP, the ability to detect radiological waste in the repository, and the existence of radiological waste in the repository.

The approach is a form of scenario analysis. Futures[1] can be constructed by considering alternative projections of basic trends in society. These trends may include population growth, technological development, and the use and scarcity of resources, among others. Transcending these factors are events that interrupt, modify, or reinforce the development of society. Such events include war, disease, pestilence, fortuitous discovery of new technologies, human-induced climatic changes, and so forth.

Each future specifies a picture of the characteristics of society at various times. These characteristics will, in turn, provide information about those activities that are likely to take place and pose threats to the integrity of the repository. Such activities include extractive industry, particularly mining for potash or drilling for oil and gas, and drilling for water for use in agriculture, industry, or for other purposes. Other types of intrusion include various kinds of excavation or intrusive activities not currently practiced.

From the states of societies and their potentially intrusive activities, modes of intrusion and motivations for these intrusions can be inferred. Similarly, from futures and the resulting states of society, one can assess whether knowledge concerning underground disposal of nuclear waste would exist, whether the waste itself would continue to exist, and whether a means to detect waste before or during intrusion would exist.

Four teams of future-intrusion experts will each provide a written report that will discuss societal development, describe possible futures, and establish the basis for estimating the possibilities of these futures. The teams will analyze modes of intrusion and develop quantitative (probabilistic) estimates of the frequencies of various intrusions. The likelihoods of various futures will also be estimated by the teams with assistance from an elicitation specialist.

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[1] The expert-elicitation scenarios are referred to here as "futures" to avoid confusion with scenarios developed for consequence analysis.

The marker-development experts will consider passive markers (i.e., markers that, after installation, should remain operational without further human attention) for deterring inadvertent human intrusion. These experts will be asked to define characteristics for selecting and manufacturing markers to be placed at the WIPP and to estimate the efficacy of these markers over the 10,000 years of regulatory interest. The marker characteristics should be defined so that, during the performance period, the markers and their message(s) will have a high probability of warning potential intruders of the dangers associated with the transuranic wastes within the repository. A system of several types of markers may increase the probability that warnings about the WIPP are heeded. Judgments about the likely performance of the selected marker system will depend on the possible future states of society (identified by the future-intrusion experts) and on the physical changes that the region surrounding the WIPP could undergo.

Determining characteristics for markers, one product of the marker-development activity, will require assessing specific marker performance for various modes of intrusion under various natural and manmade processes that may destroy or neutralize the markers. Intrusion modes identified by the future-intrusion experts will be provided to the expert panel working on characteristics for markers. The marker-development experts may, however, identify additional intrusion modes.

The marker-development panel will be asked to probabilistically estimate the performance of various types of markers. These estimates will be formally elicited.

The probability estimates of both the marker-development and future-intrusion experts will be documented, processed, and returned to the experts for comment and review. Following concurrence by the experts, the results will be documented for the performance assessment.

Expert Selection

Expert selection for the future-intrusion and marker-development panels has been a major activity. For the future-intrusion panel, 16 experts organized into four four-member teams have been selected. Their backgrounds span a variety of social and physical sciences, including, for example, futures studies, demography, mining engineering, agricultural science, and resource economics. For the marker-development panel, 12 experts and one consultant organized into one six-member and one seven-member team have been selected. Their backgrounds include anthropology, archaeology, cognitive psychology, linguistics, materials science, astronomy, and architecture. The three steps in this process were nominator identification, nominee identification, and selection of experts.

Persons with sufficient knowledge to nominate individuals to serve on the future-intrusion and marker-development panels were identified. The nominators were identified through contacts with professional organizations, government organizations, and private industry. In addition, nominators were identified through literature searches in various areas such as futures research and marker development for nuclear waste repositories. Once the nominators were identified, they were formally requested to nominate candidates for the panels. Nominations were solicited from 71 nominators for the future-intrusion panel and from 75 nominators for the marker-development panel.

The nominators, who could also nominate themselves, submitted a total of 126 nominations for the future-intrusion panel and 92 nominations for the marker-development panel. The nominees were requested to submit a description of their interests and any special qualifications relevant to the particular activity, along with a curriculum vitae. Letters of interest were received from 70 nominees for the future-intrusion panel and 57 for the marker-development panel.

The selection committee for each panel was composed of three individuals who are not members of the Sandia National Laboratories staff. Each member of the selection committees evaluated the nominees on the following criteria: tangible evidence of expertise; professional reputation; availability and willingness to participate; understanding of the general problem area; impartiality; lack of economic or personal stake in the potential findings; balance among team members to provide each team the needed breadth of expertise; physical proximity to other participants to facilitate interactions between team members; and balance among all participants to ensure adequate representation of various constituent groups.

FEDERAL OWNERSHIP

The DOE or some successor agency will retain ownership and administrative control over the land in accordance with Appendix B of the Standard. The federal agency responsible for the land will institute regulations that appropriately restrict land use and development. The Bureau of Land Management has obtained federal control of the remaining sections of former state trust lands within the boundary.

RECORDS

Records will be preserved of the disposal site and its contents. Though no expert-elicitation effort has yet been planned on what types of records should be preserved, the future-intrusion panel will estimate how effective records would be in preventing inadvertent human intrusion. Records should specify techniques for borehole plugging should exploratory drilling cause an intrusion. Such techniques could be incorporated into the legal records along with the description and location of the disposal system. The records could also contain a warning about the potential effects of drilling through the repository and into pressurized brine in the Castile Formation.

Multiple Barriers

The Standard requires that both natural and engineered barriers be used as part of the isolation system. At the WIPP, natural barriers include both the salt formation, with its favorable characteristics, and the geohydrologic setting. Engineered barriers include backfills and seals that isolate volumes of wastes. The effectiveness of these barriers is being modeled for the performance assessment. The objective is to provide a disposal system that isolates the radioactive wastes to the levels required in the Standard. In addition, the DOE has commissioned an Engineered Alternative Task Force to evaluate additional engineering measures for the WIPP should such measures be necessary.

Natural Resources

The Standard requires that locations containing recoverable resources not be used unless the favorable characteristics of a location can be shown to compensate for the greater likelihood of being disturbed in the future. The WIPP Project met this requirement when the site was selected, and the Project will issue a finding to that effect. The value of natural resources whose extraction must be foregone was considered in the WIPP siting decision. That value was weighed against other alternatives in the *FEIS* (U.S. DOE, 1980a). The DOE intends to summarize the factors considered in the site selection in the "finding" report.

Waste Removal

The Standard requires that locating and recovering the waste for a reasonable period of time after disposal be technologically feasible. In promulgating the Standard, the EPA stated that "<u>any</u> current concept for a mined geologic repository meets this requirement <u>without</u> any additional procedures or design features" (U.S. EPA, 1985, p. 38082). Thus, the WIPP satisfies this requirement.

IX. GROUNDWATER PROTECTION REQUIREMENTS

The text of Chapter IX is preceded by a synopsis that simplifies concepts presented in Chapter IX. Detailed information about those concepts is in the text following the synopsis.

Synopsis

Groundwater Protection Requirements require the disposal system to provide a reasonable expectation that concentrations of radionuclides in a "special source of ground water" will not exceed specified values.

The Groundwater Protection Requirements would be relevant to the WIPP only if a "special source of ground water" were present at the WIPP, but none exists there.

Criteria for Special Sources of Groundwater

Presence of Class I Groundwater

For Class I groundwater to be present at the WIPP, the groundwater resource must be highly vulnerable to contamination because of the hydrogeological characteristics of the areas under which it occurs.

In addition, the groundwater must either be an irreplaceable source of drinking water, or the groundwater must be ecologically vital.

Studies indicate that such groundwater is not present in the vicinity of the WIPP.

Drinking Water Supply

At the time the DOE chose the WIPP location and at present, no source of water within 5 km (3 mi) of the maximum allowable extent of the controlled area was supplying drinking water for thousands (or even tens) of persons.

Alternative Source of Drinking Water

Because no Class I groundwater is present in the vicinity of the WIPP, no alternative source of drinking water is needed.

The Groundwater Protection Requirements (§ 191.16) require the disposal system to provide a reasonable expectation that radionuclide concentrations in a "special source of ground water" will not exceed values specified in the regulation. This chapter shows that the requirement is not relevant to the WIPP because no groundwater near the WIPP satisfies the definition of special source of groundwater.

A special source of groundwater is defined as:

> ... those Class I groundwaters identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that the Department chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the NWPA); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population. (§ 191.12(o))

In accordance with the above definition, the Groundwater Protection Requirements would be relevant to the WIPP only if <u>all</u> of the criteria were met (Figure IX-1).

The following sections address these criteria.

Criteria for Special Sources of Groundwater

In its *Ground-Water Protection Strategy* (U.S. EPA, 1984), the EPA establishes groundwater protection policies for three classes of groundwater. The class definitions were developed to reflect the value of the groundwater and its

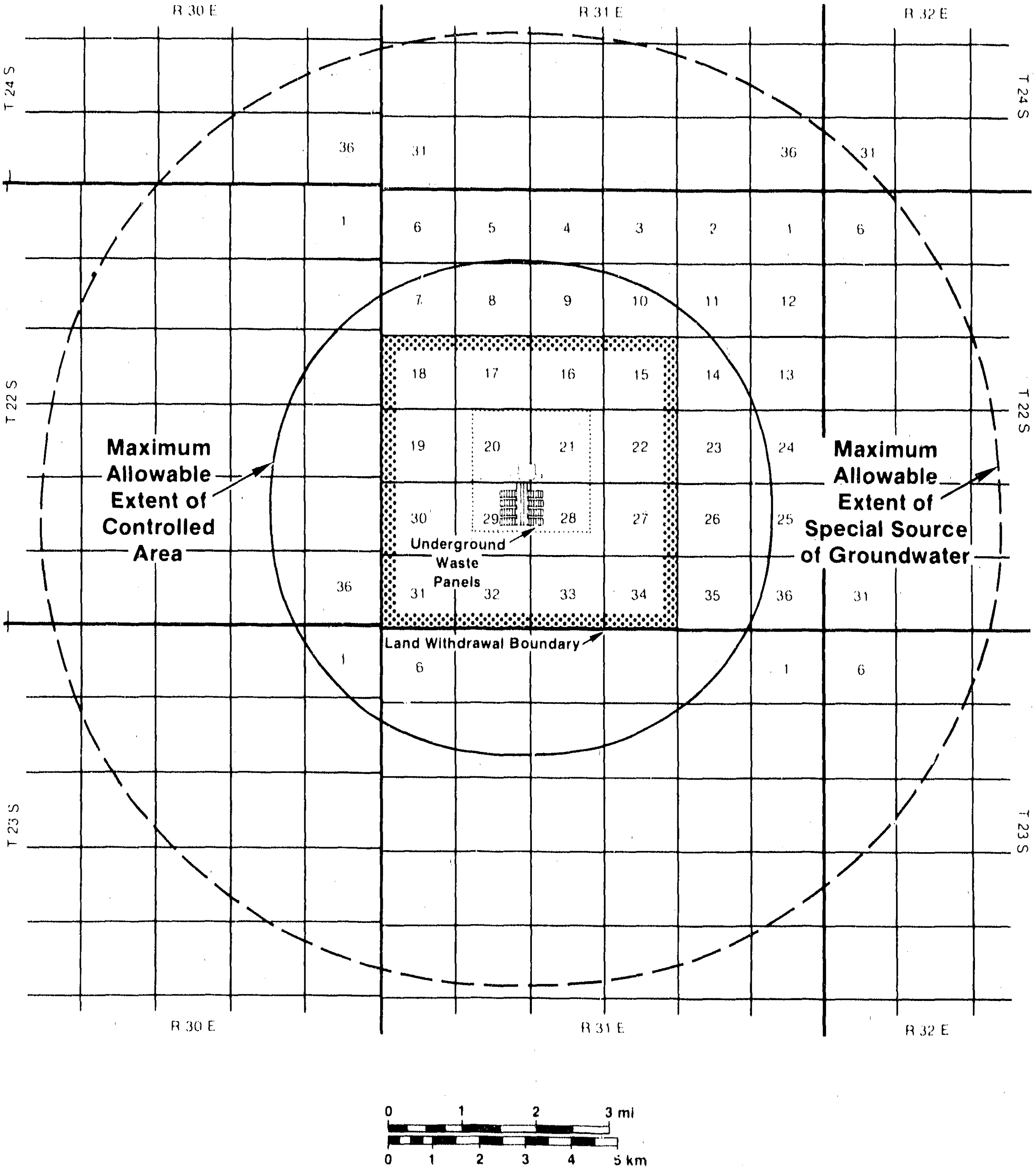

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Figure IX-1. Illustration of Certain Definitions (from U.S. DOE, 1989a). The dashed line, drawn 5 km (3 mi) from the maximum allowable extent of the controlled area (§ 191.12(g)) shows the maximum area in which the occurrence of a special source of groundwater (§ 191.12(o)) is of regulatory interest.

vulnerability to contamination. The classes apply to groundwater having significant water resource value. Class I groundwaters (U.S. EPA, 1984) are defined as follows:

> Certain ground-water resources are in need of special protective measures. These resources are defined to include those that are highly vulnerable to contamination because of the hydrogeological characteristics of the areas under which they occur. Examples of hydrogeological characteristics that cause groundwater to be vulnerable to contamination are high hydraulic conductivity (karst formations, sand and gravel aquifers) or recharge conditions (high water table overlain by thin and highly permeable soils). In addition, special groundwaters are characterized by one of the following two factors:
>
> (1) Irreplaceable source of drinking water. These include groundwater located in areas where there is no practical alternative source of drinking water (islands, peninsulas, isolated aquifers over bed rock) or an insufficient alternative source for a substantial population; or
>
> (2) Ecologically vital, in that the groundwater contributes to maintaining either the base flow or water level for a particularly sensitive ecological system that, if polluted, would destroy a unique habitat (e.g., those associated with wetlands that are habitats for unique species of flora and fauna or endangered species).

Based upon this EPA definition, for Class I groundwater to be present at the WIPP, the groundwater resource must be highly vulnerable to contamination because of the hydrogeological characteristics of the areas under which the resource occurs, including areas of high hydraulic conductivity or areas of groundwater recharge. Either of the following must also be true: the groundwater must be an irreplaceable source of drinking water, or the groundwater must be ecologically vital.

The hydrogeological characteristics of the WIPP have been evaluated through extensive ongoing investigations dating to 1975 (U.S. DOE, 1990e). Groundwater quality and the hydrologic conductivity of water-bearing units at the WIPP are monitored and reported annually (U.S. DOE, 1989b).

The most transmissive hydrologic unit in the WIPP area is the Culebra Dolomite Member of the Rustler Formation. Hydraulic properties of the Culebra Dolomite have been calculated from test holes in the vicinity of the WIPP site (U.S. DOE, 1990e). The Culebra is a confined unit; transmissivities range from 7.5×10^{-8} to 8×10^{-5} m^2/s (7×10^{-2} to 74 ft^2/d). Horizontal groundwater flow in the Culebra is generally to the south along a decreasing gradient at a very slow rate. Studies of the hydrogeology in the vicinity of the WIPP support a conclusion that the area does not exhibit the characteristic of high hydraulic conductivity.

The Culebra is overlain by an anhydrite unit having a lower hydraulic conductivity than the Culebra. This unit confines the Culebra hydraulically from overlying rock. In wells located to the east of Livingston Ridge, the depth to the middle of the Culebra is consistently greater than 125 m below the ground surface (Marietta et al., 1989). Lappin et al. (1989) concluded that available data indicate that "modern flow directions within the Rustler Formation, including the Culebra, do not reflect flow from a modern recharge area to a modern discharge area ...."

This information supports a conclusion that the hydrologic system in the vicinity of the WIPP is not a significant groundwater recharge zone. In addition, the area is not characterized by a high water table overlain by thin and highly permeable soils. Much of the area includes shallow (10 ft or less below the ground surface) underlying beds of caliche and siltstone that are believed to prevent large volumes of water from moving downward (U.S. DOE, 1990e).

No groundwater near the WIPP is highly vulnerable to contamination. Even if such groundwater was present, it would not be classified as Class I unless either the second or third criterion was also met.

Low yields of water-bearing units and high concentrations of total dissolved solids in groundwater in the vicinity of the site severely limit groundwater use. Water from the Culebra Dolomite is restricted mostly to stock watering; none is used for domestic purposes. Total dissolved solids concentrations in Culebra groundwater in the vicinity range from 3,200 to 420,000 mg/ℓ (Marietta et al., 1989). Groundwater in the vicinity does not represent an "irreplaceable source of drinking water ... for a substantial population ...," so the first factor necessary for Class I groundwaters is not met.

Groundwater at the site is also not "ecologically vital" as described in the second factor characterizing Class I groundwater. Groundwater at the site does not contribute "to maintaining base flow or water level for a particularly sensitive ecological system that, if polluted, would destroy a unique habitat ...."

DRINKING WATER SUPPLY

Class I groundwater is not present in the vicinity of the WIPP and, as a consequence of this, the Groundwater Protection Requirements are not relevant to the WIPP. If Class I groundwaters were present, however, the requirements would be relevant only if the groundwater was supplying drinking water to thousands of persons at the date DOE selected the site for development of the WIPP *and* if these groundwaters were irreplaceable.

At the time the DOE chose the WIPP location, no source of water (including Class I groundwaters) within 5 km (3 mi) of the maximum allowable extent of the controlled area was supplying drinking water for thousands (or even tens) of persons, a fact that remains true today. Thus, even if Class I groundwaters were present, the requirements of § 191.16 would not be relevant to the WIPP.

ALTERNATIVE SOURCE OF DRINKING WATER

As described above, no Class I groundwater is present in the vicinity of the WIPP. No population of thousands of people is in the vicinity of the WIPP; therefore, no alternative source of drinking water is needed.

X. COMPARISON TO THE STANDARD

This preliminary performance assessment cannot be compared to the requirements of the Standard to interpret defensibly whether the WIPP disposal system complies with Subpart B because the disposal system is not adequately characterized, and necessary conceptual models, computer programs, and data bases are incomplete. Instead, the discussion in this chapter examines the adequacy of the information available for producing a defensible comparison to the Containment Requirements and the Individual Protection Requirements. Defensibility of performance assessment will be determined primarily by qualitative judgment regarding "reasonable expectation" (§ 191.13(b) and § 191.15). The Assurance Requirements and the Groundwater Protection Requirements are also considered here. All questions of adequacy inherently depend on the Standard: this evaluation is based on the 1985 version of the Standard.

Each section is evaluated as to whether the available information is sufficient to judge adequacy. The utility of the compliance assessment system is conditional on how well we understand the disposal system, and is reflected here for the natural barriers of the controlled area and the engineered barriers of the repository/shaft system.

Under ideal conditions, the performance assessment would be exhaustive. An exhaustive performance assessment would require defining the uncertainty in all conceptual models, developing mathematical models and computer programs for all components and subsystems, benchmarking all computational models, and measuring all data.

A practical performance assessment requires identifying all the components and subsystems, then determining with sensitivity and uncertainty analyses which components and subsystems are critical to disposal-system performance. Appropriate mathematical models and computer programs are developed for the critical components and subsystems. Uncertainties in the conceptual models, mathematical models, and data sets for the critical components and subsystems must be understood in detail.

The WIPP performance assessment is taking a practical approach. Critical components and subsystems are being identified by iterative uncertainty and sensitivity analyses using the best available models. All critical computational models and data sets must be satisfactorily completed before this performance assessment can be defensibly judged to be complete.

The performance of the WIPP can be compared to the Standard when (U.S. DOE, 1990a):

The complete set of significant scenarios with probabilities of occurrence has been defined.

The compliance assessment system is considered adequate, is operational, and record keeping is adequate to support repetition or modification of each simulation.

The data sets have undergone quality assurance, and the computational models and systems of models have been validated to the extent possible.

The final analyses are complete, and a peer review process has affirmed that the analyses are adequate.

Formal comparison to determine compliance should be based on comprehensive, practical performance assessments that incorporate all critical elements, results of the in situ tests, and other appropriate refinements in the system. As test results and system refinements are incorporated into the performance assessment, their influence on the performance measures (i.e., the CCDFs and doses) should be evaluated. If successive, iterative assessments converge to a stable CCDF, the performance assessment can be considered complete.

Containment Requirements

CAMCON can be used for sensitivity and uncertainty analyses, and is adequate for preliminary performance studies. The bases for the compliance assessment system (Table V-7) are inadequate at this stage for a defensible comparison to the 1985 Standard because many important modules are in preliminary or intermediate stages of understanding or readiness (Table X-1).

Individual Protection Requirements

Because the compliance assessment system must be used to predict releases to the accessible environment for undisturbed performance, a defensible comparison to the Standard cannot be prepared until the bases of the system are judged adequate.

Preliminary analyses and related deterministic analyses suggest that no releases will occur; therefore, dose predictions are not likely to be required.

TABLE X-1. STATUS OF PERFORMANCE ASSESSMENT BASES FOR DEFENSIBLY COMPLETING FINAL COMPARISON TO THE STANDARD, CONDITIONAL ON 1990 COMPLIANCE ASSESSMENT SYSTEM[1]

MODULE	STATUS[2]		
	Preliminary	Intermediate	Advanced
RADIONUCLIDE TRANSPORT IN NON-SALADO STRATA			
Geostatistics		X	
2-D Groundwater		X	
3-D Groundwater	X		
2-D Transport	X		
3-D Transport	X		
Climate Variability	X		
FAR-FIELD BRINE INFLOW AND GAS DISSIPATION PROCESSES IN SALADO/CASTILE FORMATION			
2-Phase Gas Flow	X		
Brine and Gas Pockets		X	
WASTE PANEL			
Closure and Compaction		X	
Decay Model		X	
2-Phase Gas and Radionuclide Transport	X		
Human Intrusion Borehole			X
WIPP SEAL SYSTEMS			
Panel Seal	X		
Shaft Seal	X		
Salado Formation	X		

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[1] Defensibility of performance assessment will be determined primarily by qualitative judgment regarding reasonable expectation (§ 191.13(b), § 191.15).

[2] This status evaluation assumes all components and subsystems are equally necessary pending sensitivity analyses to establish priorities.

Assurance Requirements

Each of the six requirements is discussed here.

ACTIVE INSTITUTIONAL CONTROLS

Available information is not sufficient for judging adequacy. Performance assessment simulations begin 100 years after decomissioning, thus assuming active controls for the maximum period allowed by the Standard.

DISPOSAL SYSTEM MONITORING

Available information is not sufficient for judging adequacy.

PASSIVE INSTITUTIONAL CONTROLS

Passive markers have not been designed, but will be assumed to deter human intrusion in performance assessment calculations when marker specifications are available.

The land withdrawal has not been enacted by the U.S. Congress.

The message content of records has not been determined.

MULTIPLE BARRIERS

The natural barrier provided by the Salado Formation and the engineered barriers are adequate for undisturbed performance, provided gas pressurization does not have unexpected effects on the disposal system. The bases for the compliance assessment system are currently inadequate to determine whether the barriers are adequate for disturbed performance.

NATURAL RESOURCES

A finding that the WIPP Project has met the requirement has not been published.

WASTE REMOVAL

EPA found that current plans for mined geologic repositories meet this requirement without additional design (U.S. EPA, 1985). No further action should be necessary.

Groundwater Protection Requirements

This requirement is not relevant to the WIPP disposal system. No further action should be necessary.

XI. RECOMMENDATIONS

This chapter summarizes the work remaining to be completed to develop an adequate basis for defensibly evaluating compliance with Subpart B of the Standard. Refer to the *WIPP Test Phase Plan* (U.S. DOE, 1990d) for activities identified prior to this preliminary assessment and to Tables V-7 and X-1 for the status of many of those activities. As a result of this preliminary performance assessment, we have identified several important activities as necessary for a defensible preliminary assessment. These activities are listed here, followed by recommendations for proceeding with the compliance evaluation for each requirement in Subpart B.

To complete a stable CAMCON system, finish developing:

a geostatistical module for properly including residual uncertainty in data for the Culebra Dolomite Member of the Rustler Formation and perhaps for other units (see "Calibrating Groundwater Flow Models for the Culebra Dolomite Member" in Chapter V)—pilot program already in CAMCON.

a two-phase Darcy-flow module for gas and brine flow in waste panels and surrounding Salado Formation that can simulate human intrusion scenarios accurately and with short enough execution times for Monte-Carlo simulation using LHS (see "Closure, Flow, and Room/Waste Interactions" in Chapter V)—pilot program using multigrid algorithms already available.

a 3-D groundwater module with short-enough execution times for Monte-Carlo simulation using LHS—program now available for inclusion in CAMCON.

To define inventory-related inputs, develop:

RH-waste inventory,

final RH-waste emplacement design, and

waste-form characterization for CH- and RH-waste after compaction to assess variability on a panel scale (larger than a drum-scale) for pdf construction—load management is related to this variability.

To finish scenario and probability-assignment tasks:

estimate probabilities for frequencies of intrusion,

identify passive marker systems to be used, and

estimate probabilities of intrusion with markers as deterrents.

Define or estimate and include conceptual model uncertainty, incorporating appropriate parameter value distributions as they become available, especially for important submodels:

radionuclide transport in overlying fluid-bearing units,

gas generation,

climate variability and regional recharges,

climate variability and local recharge,

coupled creep and two-phase Darcy flow in Salado Formation,

coupled fracture flow and two-phase Darcy flow in Salado Formation interbeds,

coupled effective critical bulk-shear strength and cavings removal,

Darcy flow assumptions in Salado Formation,

human intrusion boreholes and future states of society, and

coupled stratified flow and retardation in a single unit such as the Culebra Dolomite.

Containment Requirements

Continue using the compliance assessment system for sensitivity and uncertainty analyses, and continue developing the modules to support comprehensive, defensible performance assessments.

Individual Protection Requirements

Re-evaluate whether dose calculations are necessary when the compliance assessment system and its bases are judged complete and the Standard is repromulgated.

Assurance Requirements

Each of the six requirements is discussed here.

ACTIVE INSTITUTIONAL CONTROLS

Update the Assurance Requirements Plan (U.S. DOE, 1987a), adding plans for at least 100 years of active control.

DISPOSAL SYSTEM MONITORING

Update the Assurance Requirements Plan (U.S. DOE, 1987a).

PASSIVE INSTITUTIONAL CONTROLS

Complete expert-judgment elicitations and design markers.

Complete the proposed land withdrawal.

Determine the message content and types of records.

Update the Assurance Requirement Plan (DOE, 1987a).

MULTIPLE BARRIERS

Determine whether the natural barriers of the controlled area and the engineered barriers of the repository/shaft system are adequate for disturbed performance.

NATURAL RESOURCES

Publish a finding that the WIPP Project has met the requirement.

Groundwater Protection Requirements

Re-evaluate whether the requirements are relevant to the WIPP when the Standard is repromulgated.

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APPENDIX A:
TITLE 40, CODE OF FEDERAL REGULATIONS, SUBCHAPTER F, PART 191

APPENDIX A:
TITLE 40, CODE OF FEDERAL REGULATIONS
SUBCHAPTER F—RADIATION PROTECTION PROGRAMS

PART 191—ENVIRONMENTAL RADIATION PROTECTION STANDARDS FOR MANAGEMENT AND DISPOSAL OF SPENT NUCLEAR FUEL, HIGH-LEVEL AND TRANSURANIC RADIOACTIVE WASTES

Subpart A—Environmental Standards for Management and Storage

Subpart B—Environmental Standards for Disposal

Authority: The Atomic Energy Act of 1954, as amended; Reorganization Plan No. 3 of 1970; and the Nuclear Waste Policy Act of 1982.

Subpart A—Environmental Standards for Management and Storage

§ 191.01 Applicability.

This Subpart applies to:

(a) Radiation doses received by members of the public as a result of the management (except for transportation) and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at any facility regulated by the

Nuclear Regulatory Commission or by Agreement States, to the extent that such management and storage operations are not subject to the provisions of Part 190 of title 40; and

(b) Radiation doses received by members of the public as a result of the management and storage of spent nuclear fuel or high-level or transuranic wastes at any disposal facility that is operated by the Department of Energy and that is not regulated by the Commission or by Agreement States.

§ 191.02 Definitions.

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of Part 190.

(a) "Agency" means the Environmental Protection Agency.

(b) "Administrator" means the Administrator of the Environmental Protection Agency.

(c) "Commission" means the Nuclear Regulatory Commission.

(d) "Department" means the Department of Energy.

(e) "NWPA" means the Nuclear Waste Policy Act of 1982 (Pub. L. 97-425).

(f) "Agreement State" means any State with which the Commission or the Atomic Energy Commission has entered into an effective agreement under subsection 274b of the Atomic Energy Act of 1954, as amended (68 Stat. 919).

(g) "Spent nuclear fuel" means fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

(h) "High-level radioactive waste," as used in this Part, means high-level radioactive waste as defined in the Nuclear Waste Policy Act of 1982 (Pub. L. 97-425).

(i) "Transuranic radioactive waste," as used in this Part, means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) High-level radioactive wastes; (2) wastes that the Department has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this Part; or (3) wastes that the Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.

(j) "Radioactive waste," as used in this Part, means the high-level and transuranic radioactive waste covered by this Part.

(k) "Storage" means retention of spent nuclear fuel or radioactive wastes with the intent and capability to readily retrieve such fuel or waste for subsequent use, processing, or disposal.

(l) "Disposal" means permanent isolation of spent nuclear fuel or radioactive wastes from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such fuel or waste. For example, disposal of waste in a mined geologic repository occurs when all of the shafts to the repository are backfilled and sealed.

(m) "Management" means any activity, operation, or process (except for transportation) conducted to prepare spent nuclear fuel or radioactive waste for storage or disposal, or the activities associated with placing such fuel or waste in a disposal system.

(n) "Site" means an area contained within the boundary of a location under the effective control of persons possessing or using spent nuclear fuel or radioactive waste that are involved in any activity, operation, or process covered by this Subpart.

(o) "General environment" means the total terrestrial, atmospheric, and aquatic environments outside sites within which any activity, operation, or process associated with the management and storage of spent nuclear fuel or radioactive waste is conducted.

(p) "Member of the public" means any individual except during the time when that individual is a worker engaged in any activity, operation, or process that is covered by the Atomic Energy Act of 1954, as amended.

(q) "Critical organ" means the most exposed human organ or tissue exclusive of the integumentary system (skin) and the cornea.

§ 191.03 Standards.

(a) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities regulated by the Commission or by Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from: (1) Discharges of radioactive material and direct radiation from such management and storage and (2) all operations covered by Part 190; shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other critical organ.

(b) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities for the disposal of such fuel or waste that are operated by the Department and that are not regulated by the Commission or Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from discharges of radioactive material and direct radiation from such management and storage shall not exceed 25 millirems to the whole body and 75 millirems to any critical organ.

§ 191.04 **Alternative standards.**

(a) The Administrator may issue alternative standards from those standards established in 191.03(b) for waste management and storage activities at facilities that are not regulated by the Commission or Agreement States if, upon review of an application for such alternative standards:

(1) The Administrator determines that such alternative standards will prevent any member of the public from receiving a continuous exposure of more than 100 millirems per year dose equivalent and an infrequent exposure of more than 500 millirems dose equivalent in a year from all sources, excluding natural background and medical procedures; and

(2) The Administrator promptly makes a matter of public record the degree to which continued operation of the facility is expected to result in levels in excess of the standards specified in 191.03(b).

(b) An application for alternative standards shall be submitted as soon as possible after the Department determines that continued operation of a facility will exceed the levels specified in 191.03(b) and shall include all information necessary for the Administrator to make the determinations called for in 191.04(a).

(c) Requests for alternative standards shall be submitted to the Administrator, U.S. Environmental Protection Agency, 401 M Street, SW., Washington, DC 20460.

§ 191.05 **Effective date.**

The standards in this Subpart shall be effective on November 18, 1985.

Subpart B—Environmental Standards for Disposal

§ 191.11 Applicability.

(a) This Subpart applies to:

(1) Radioactive materials released into the accessible environment as a result of the disposal of spent nuclear fuel or high-level or transuranic radioactive wastes;

(2) Radiation doses received by members of the public as a result of such disposal; and

(3) Radioactive contamination of certain sources of ground water in the vicinity of disposal systems for such fuel or wastes.

(b) However, this Subpart does not apply to disposal directly into the oceans or ocean sediments. This Subpart also does not apply to wastes disposed of before the effective date of this rule.

§ 191.12 Definitions.

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of this Part.

(a) "Disposal system" means any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal.

(b) "Waste," as used in this Subpart, means any spent nuclear fuel or radioactive waste isolated in a disposal system.

(c) "Waste form" means the materials comprising the radioactive components of waste and any encapsulating or stabilizing matrix.

(d) "Barrier" means any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

(e) "Passive institutional control" means: (1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.

(f) "Active institutional control" means: (1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance.

(g) "Controlled area" means: (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.

(h) "Ground water" means water below the land surface in a zone of saturation.

(i) "Aquifer" means an underground geological formation, group of formations, or part of a formation that is capable of yielding a significant amount of water to a well or spring.

(j) "Lithosphere" means the solid part of the Earth below the surface, including any ground water contained within it.

(k) "Accessible environment" means: (1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area.

(l) "Transmissivity" means the hydraulic conductivity integrated over the saturated thickness of an underground formation. The transmissivity of a series of formations is the sum of the individual transmissivities of each formation comprising the series.

(m) "Community water system" means a system for the provision to the public of piped water for human consumption, if such system has at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.

(n) "Significant source of ground water," as used in this Part, means: (1) An aquifer that: (i) Is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface; (iii) has a transmissivity greater than 200 gallons per day per foot, provided that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than 2 gallons per day per square foot; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of this Subpart.

(o) "Special source of ground water," as used in this Part, means those Class I ground waters identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that the Department chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the NWPA); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

(p) "Undisturbed performance" means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

(q) "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.

(r) "Heavy metal" means all uranium, plutonium, or thorium placed into a nuclear reactor.

(s) "Implementing agency," as used in this Subpart, means the Commission for spent nuclear fuel or high-level or transuranic wastes to be disposed of in facilities licensed by the commission in accordance with the Energy Reorganization Act of 1974 and the Nuclear Waste Policy Act of 1982, and it means the Department for all other radioactive wastes covered by this Part.

§ 191.13 Containment requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that 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 according to Table 1 (Appendix A); and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

(b) 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 the record before the implementing agency, that compliance with 191.13(a) will be achieved.

§ 191.14 **Assurance requirements.**

To provide the confidence needed for long-term compliance with the requirements of 191.13, disposal of spent nuclear fuel or high-level or transuranic wastes shall be conducted in accordance with the following provisions, except that these provisions do not apply to facilities regulated by the Commission (see 10 CFR Part 60 for comparable provisions applicable to facilities regulated by the Commission):

(a) Active institutional controls over disposal sites should be maintained for as long a period of time as is practicable after disposal; however, performance assessments that assess isolation of the wastes from the accessible environment shall not consider any contributions from active institutional controls for more than 100 years after disposal.

(b) Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring.

(c) 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.

(d) Disposal systems shall use different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included.

(e) Places where there has been mining for resources, or where there is a reasonable expectation of exploration for scarce or easily accessible resources, or where there is a significant concentration of any material that is not widely available from other sources, should be avoided in selecting disposal sites. Resources to be considered shall include minerals, petroleum or natural gas, valuable geologic formations, and ground waters that are either irreplaceable because there is no reasonable alternative source of drinking water available for substantial populations or that are vital to the preservation of unique and sensitive ecosystems. Such places shall not be used for disposal of the wastes covered by this Part unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future.

(f) Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.

§ 191.15 Individual protection requirements.

Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual dose equivalent from the disposal system to any member of the public in the accessible environment to exceed 25 millirems to the whole body or 75 millirems to any critical organ. All potential pathways (associated with undisturbed performance) from the disposal system to people shall be considered, including the assumption that individuals consume 2 liters per day of drinking water from any significant source of ground water outside of the controlled area.

§ 191.16 Ground water protection requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the radionuclide concentrations averaged over any year in water withdrawn from any portion of a special source of ground water to exceed:

(1) 5 picocuries per liter of radium-226 and radium-228;
(2) 15 picocuries per liter of alpha-emitting radionuclides (including radium-226 and radium-228 but excluding radon); or
(3) The combined concentrations of radionuclides that emit either beta or gamma radiation that would produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems per year if an individual

consumed 2 liters per day of drinking water from such a source of ground water.

(b) If any of the average annual radionuclide concentrations existing in a special source of ground water before construction of the disposal system already exceed the limits in 191.16(a), the disposal system shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not increase the existing average annual radionuclide concentrations in water withdrawn from that special source of ground water by more than the limits established in 191.16(a).

§ 191.17 Alternative provisions for disposal.

The Administrator may, by rule, substitute for any of the provisions of Subpart B alternative provisions chosen after:

(a) The alternative provisions have been proposed for public comment in the **Federal Register** together with information describing the costs, risks, and benefits of disposal in accordance with the alternative provisions and the reasons why compliance with the existing provisions of Subpart B appears inappropriate;

(b) A public comment period of at least 90 days has been completed, during which an opportunity for public hearings in affected areas of the country has been provided; and

(c) The public comments received have been fully considered in developing the final version of such alternative provisions.

§ 191.18 Effective date.

The standards in this Subpart shall be effective on November 18, 1985.

Appendix A—Table for Subpart B

TABLE 1.—RELEASE LIMITS FOR CONTAINMENT REQUIREMENTS

(Cumulative releases to the accessible environment for 10,000 years after disposal)

Radionuclide	Release limit per 1,000 MTHM or other unit of waste (see notes) (curies)
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

Application of Table 1

Note 1: *Units of Waste*. The Release Limits in Table 1 apply to the amount of wastes in any one of the following:

(a) An amount of spent nuclear fuel containing 1,000 metric tons of heavy metal (MTHM) exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM;

(b) The high-level radioactive wastes generated from reprocessing each 1,000 MTHM exposed to a burnup between 25,000 MWd/MTHM and 40,000 MWd/MTHM;

(c) Each 100,000,000 curies of gamma or beta-emitting radionuclides with half-lives greater than 20 years but less than 100 years (for use as discussed in Note 5 or with materials that are identified by the Commission as high-level radioactive waste in accordance with part B of the definition of high-level waste in the NWPA);

(d) Each 1,000,000 curies of other radionuclides (i.e., gamma or beta-emitters with half-lives greater than 100 years or any alpha-emitters with half-lives greater than 20 years) (for use as discussed in Note 5 or with materials that are identified by the Commission as high-level radioactive waste in accordance with part B of the definition of high-level waste in the NWPA); or

(e) An amount of transuranic (TRU) wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years.

Note 2: *Release Limits for Specific Disposal Systems*. To develop Release Limits for a particular disposal system, the quantities in Table 1 shall be adjusted for the amount of waste included in the disposal system compared to the various units of waste defined in Note 1. For example:

(a) If a particular disposal system contained the high-level wastes from 50,000 MTHM, the Release Limits for that system would be the quantities in Table 1 multiplied by 50 (50,000 MTHM divided by 1,000 MTHM).

(b) If a particular disposal system contained three million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by three (three million curies divided by one million curies).

(c) If a particular disposal system contained both the high-level wastes from 50,000 MTHM and 5 million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by 55:

$$\frac{50{,}000\ \text{MTHM}}{1{,}000\ \text{MTHM}} + \frac{5{,}000{,}000\ \text{curies TRU}}{1{,}000{,}000\ \text{curies TRU}} = 55$$

Note 3: *Adjustments for Reactor Fuels with Different Burnup*. For disposal systems containing reactor fuels (or the high-level wastes from reactor fuels) exposed to an average burnup of less than 25,000 MWd/MTHM or greater than 40,000 MWd/MTHM, the units of waste defined in (a) and (b) of Note 1 shall be adjusted. The unit shall be multiplied by the ratio of 30,000 MWd/MTHM divided by the fuel's actual average burnup, except that a value of 5,000

MWd/MTHM may be used when the average fuel burnup is below 5,000 MWd/MTHM and a value of 100,000 MWd/MTHM shall be used when the average fuel burnup is above 100,000 MWd/MTHM. This adjusted unit of waste shall then be used in determining the Release Limits for the disposal system.

For example, if a particular disposal system contained only high-level wastes with an average burnup of 3,000 MWd/MTHM, the unit of waste for that disposal system would be:

$$1{,}000 \text{ MTHM} \times \frac{(30{,}000)}{(5{,}000)} = 6{,}000 \text{ MTHM}$$

If that disposal system contained the high-level wastes from 60,000 MTHM (with an average burnup of 3,000 MWd/MTHM), then the Release Limits for that system would be the quantities in Table 1 multiplied by ten:

$$\frac{60{,}000 \text{ MTHM}}{6{,}000 \text{ MTHM}} = 10$$

which is the same as:

$$\frac{60{,}000 \text{ MTHM}}{1{,}000 \text{ MTHM}} \times \frac{(5{,}000 \text{ MWd/MTHM})}{(30{,}000 \text{ MWd/MTHM})} = 10$$

Note 4: *Treatment of Fractionated High-Level Wastes.* In some cases, a high-level waste stream from reprocessing spent nuclear fuel may have been (or will be) separated into two or more high-level waste components destined for different disposal systems. In such cases, the implementing agency may allocate the Release Limit multiplier (based upon the original MTHM and the average fuel burnup of the high-level waste stream) among the various disposal systems as it chooses, provided that the total Release Limit multiplier used for that waste stream at all of its disposal systems may not exceed the Release Limit multiplier that would be used if the entire waste stream were disposed of in one disposal system.

Note 5: *Treatment of Wastes with Poorly Known Burnups or Original MTHM.* In some cases, the records associated with particular high-level waste streams may not be adequate to accurately determine the original metric tons of heavy metal in the reactor fuel that created the waste, or to determine the average burnup that the fuel was exposed to. If the uncertainties are such that the original amount of heavy metal or the average fuel burnup for particular high-level waste streams cannot be quantified, the units of waste derived from (a) and (b) of Note 1 shall no longer be used. Instead, the units of waste defined in (c) and (d) of Note 1 shall be used for such high-level waste streams. If the uncertainties in such information allow a range of values to be associated with the original amount of heavy metal or the average fuel burnup, then the calculations described in previous Notes will be conducted using the values that result in the smallest Release Limits, except that the Release Limits need not be smaller than those that would be calculated using the units of waste defined in (c) and (d) of Note 1.

Note 6: *Uses of Release Limits to Determine Compliance with 191.13.* Once release limits for a particular disposal system have been determined in accordance with Notes 1 through 5, these release limits shall be used to determine compliance with the requirements of 191.13 as follows. In cases where a mixture of radionuclides is projected to be released to the accessible environment, the limiting values shall be determined as follows: For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide as determined from Table 1 and Notes 1 through 5. The sum of such ratios for all the radionuclides in the mixture may not exceed one with regard to 191.13(a)(1) and may not exceed ten with regard to 191.13(a)(2).

For example, if radionuclides A, B, and C are projected to be released in amounts Q_a, Q_b, and Q_c, and if the applicable Release Limits are RL_a, RL_b, RL_c, then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$\frac{Q_a}{RL_a} + \frac{Q_b}{RL_b} + \frac{Q_c}{RL_c} < 1$$

Appendix B—Guidance for Implementation of Subpart B

[Note: The supplemental information in this appendix is not an integral part of 40 CFR Part 191. Therefore, the implementing agencies are not bound to follow this guidance. However, it is included because it describes the Agency's assumptions regarding the implementation of Subpart B. This appendix will appear in the Code of Federal Regulations.]

The Agency believes that the implementing agencies 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 implementing agencies 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 implementing agencies may choose to supplement such predictions with qualitative judgments as well. Because the procedures for determining compliance with Subpart B have not been formulated and tested yet, this appendix to the rule indicates the Agency's assumptions regarding certain issues that may arise when implementing §§ 191.13, 191.15, and 191.16. Most of this guidance applies to any type of disposal system for the wastes covered by this rule. However, several sections apply only to disposal in mined geologic repositories and would be inappropriate for other types of disposal systems.

Consideration of Total Disposal System. When predicting disposal system performance, the Agency assumes that reasonable projections of the protection expected from all of the engineered and natural barriers of a disposal system will be considered. Portions of the disposal system should not be disregarded, even if projected performance is uncertain, except for portions of the system that make negligible contributions to the overall isolation provided by the disposal system.

Scope of Performance Assessments. Section 191.13 requires the implementing agencies to evaluate compliance through performance assessments as defined in § 191.12(q). The Agency assumes that such performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. Furthermore, the performance assessments need not evaluate in detail the releases from all events and processes estimated to have a greater likelihood of occurrence. Some of these events and processes may be omitted from the performance assessments if there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

Compliance with Section 191.13. The Agency assumes that, whenever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with § 191.13 into a "complementary cumulative distribution function" that indicates the probability of exceeding various levels of cumulative release. When the uncertainties in parameters are considered in a performance assessment, the effects of the uncertainties considered can be incorporated into a single such distribution function for each disposal system considered. The Agency 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).

Compliance with Sections 191.15 and 191.16. When the uncertainties in undisturbed performance of a disposal system are considered, the implementing agencies need not require that a very large percentage of the range of estimated radiation exposures or radionuclide concentrations fall below limits established in §§ 191.15 and 191.16, respectively. The Agency assumes that compliance can be determined based upon "best estimate" predictions (e.g., the mean or the median of the appropriate distribution, whichever is higher).

Institutional Controls. To comply with § 191.14(a), the implementing agency will assume that none of the active institutional controls prevent or reduce radionuclide releases for more than 100 years after disposal. However, the Federal Government is committed to retaining ownership of all disposal sites for spent nuclear fuel and high-level and transuranic radioactive wastes and will establish appropriate markers and records, consistent with § 191.14(c). The Agency assumes that, as long as such passive institutional controls endure and are understood, they: (1) can be effective in deterring systematic or persistent exploitation of these disposal sites; and (2) can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the implementing agency. However, the Agency believes that passive institutional controls can never be assumed to eliminate the chance of inadvertent and intermittent human intrusion into these disposal sites.

Consideration of Inadvertent Human Intrusion into Geologic Repositories. The most speculative potential disruptions of a mined geologic repository are those associated with inadvertent human intrusion. Some types of intrusion would have virtually no effect on a repository's containment of waste. On the other hand, it is possible to conceive of intrusions (involving widespread societal loss of knowledge regarding radioactive wastes) that could result in major disruptions that no reasonable repository selection or design precautions could alleviate. The Agency 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. Furthermore, the implementing agencies 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.

Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories. 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 Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations, or more than 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations. Furthermore, the Agency assumes that the consequences of such inadvertent drilling need not be assumed to be more severe than: (1) Direct release to the land surface of all the ground water in the repository horizon that would promptly flow through the newly created borehole to the surface due to natural lithostatic pressure—or (if pumping would be required to raise water to the surface) release of 200 cubic meters of ground water pumped to the surface if that much water is readily available to be pumped; and (2) creation of 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.

APPENDIX B:
REFERENCE DATA BASE

The Reference Data Base for 1990 is available in:

Rechard, R. P., H. J. Iuzzolino, and J. S. Sandha. 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990).* SAND89-2408. Albuquerque, NM: Sandia National Laboratories.

APPENDIX C:
COMPUTATIONAL DATA BASE

APPENDIX C:
COMPUTATIONAL DATA BASE

Data presented here are based on those reported by Rechard et al., 1990a.

For all simulations summarized in Chapter VI, parameter values were selected from the ranges and distributions given in Table C-1 using a Latin hypercube sampling (LHS) technique. Not all parameters were sampled for all simulations. Values for hydraulic conductivity in the Culebra Dolomite are given for two different sets of zones. Both are based on well data reported by Cauffman et al. (1990). One set of zones (zones 1 - 8) was derived directly from observed well data, and the other (zones A through M) includes data from pilot points as determined by LaVenue et al. (1990). Figures C-1 and C-2 show the hydraulic conductivity zones for each set mapped on the regional SECO domain used in these calculations. Conductivity values for zones not used in these simulations can be found in Rechard et al. (1990a).

For simulations of the E1, E2, and E1E2 scenarios, 40 sets (vectors) of sampled values were generated from the assigned probability density functions for 29 variables. Table C-2 identifies the 29 variables and lists the sampled values that comprise the 40 vectors. Using the hydraulic conductivity zones determined without pilot points, conductivity values for the Culebra Dolomite were assigned separately for each of the six zones in which flow affected performance.

For simulations assuming a Poisson distribution for multiple intrusions, 70 vectors were generated from 51 variables (Tables C-3 and C-4). Using the hydraulic conductivity zones determined with pilot points, conductivity values were sampled separately for each of 10 zones in which flow affected performance (Figure C-2). Additional variables not considered for the three-scenario simulations included the number of intrusions, the time of intrusion for each intrusion event, and the location of each intrusion event. Up to 13 intrusions were allowed, although in this sample a maximum of 9 intrusions occurred. Location was defined by dividing the waste-storage areas of the repository, including both rooms and drifts, into 144 "rooms" of approximately equal area.

Simulations of undisturbed performance are unchanged from Marietta et al. (1989), and results of the 50-vector, 14-variable sampling are reproduced here (Table C-5; unchanged from Table D-1 of Marietta et al., 1989).

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
1. Salado Capacitance (Pa^{-1})	Lognormal pdf	1×10^{-11} to 1×10^{-10}	Assigned by principal investigator
2. Salado Permeability (m^3)	Piecewise Linear cdf	1×10^{-22} to 3×10^{-20}	MEF*-empirical percentiles from data provided by principal investigator
3. Salado Pressure (MPa)	Uniform pdf	7 to 15	MEF-bound provided by principal investigators
4. Room-Waste Solubility (all radionuclide species, kg/kg)	Loguniform pdf	2.4×10^{-10} to 2.4×10^{-4}	Assigned by principal investigator
5. Room-Time of First Intrusion	Modified Exponential pdf	3.16×10^{9} to 3.6×10^{11}	Appendix C of Tierney, in prep.
6. Brine Pocket Initial Pressure (MPa)	Piecewise Linear cdf	7 to 17.4	MEF-bounds and median provided by principal investigator
7. Borehole Permeability m^2	Lognormal pdf	1×10^{-14} to 1×10^{-11}	Freeze and Cherry, 1979
8. Borehole Porosity (dimensionless)	Normal pdf	0.25 to 0.5	Freeze and Cherry, 1979
9. Brine Pocket Bulk Volume (m^3)	Uniform pdf	4.8×10^{3} to 1.4×10^{7}	MEF-bounds provided by principal investigator
10. Culebra Tortuosity (dimensionless)	Piecewise Linear cdf	0.03 to 0.33	MEF-empirical percentiles from data in Tables E-9 of Lappin et al., 1989
11. Culebra Diffusion Coefficient (all radionuclide species, m^2/s)	Uniform pdf	4.8×10^{-11} to 4.3×10^{-10}	MEF-bounds are maximum and minimum of values given in Table A-8 of Rechard et al., 1990b
12. Culebra Fracture Spacing (m)	Piecewise Linear cdf	0.25 to 7	MEF-bounds and median provided by principal investigator

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*Maximum Entropy Formalism; see Tierney, 1990 for additional explanation

Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS (continued)

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
13. Culebra Recharge Factor (dimensionless)	Uniform pdf	1 to 2	Marietta et al., in prep.
14. Culebra Precipitation Factor (dimensionless)	Uniform pdf	1 to 2	Marietta et al., in prep.
15. Borehole cross-sectional area (m^2)	Empirical cdf	1.1×10^{-2} to 1.6×10^{-1}	Data provided by principal investigator
16. Culebra Matrix Retardation Factor for Plutonium (dimensionless)	Piecewise Linear cdf	1 to 1.6×10^4	MEF*-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
17. Culebra Matrix Retardation Factor for Americium (dimensionless)	Piecewise Linear cdf	1 to 5.6×10^3	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
18. Culebra Matrix Retardation Factor for Neptunium (dimensionless)	Piecewise Linear cdf	1 to 1.5×10^2	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
19. Culebra Matrix Retardation Factor for Uranium (dimensionless)	Piecewise Linear cdf	1 to 1.1×10^2	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
20. Culebra Fracture Retardation Factor for Plutonium (dimensionless)	Piecewise Linear cdf	1 to 5×10^4	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator

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*Maximum Entropy Formalism; see Tierney, 1990 for additional explanation

Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS (continued)

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
21. Culebra Fracture Retardation Factor for Americium (dimensionless)	Piecewise Linear cdf	1 to 5.1×10^3	MEF*-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
22. Culebra Fracture Retardation Factor for Neptunium (dimensionless)	Piecewise Linear cdf	1 to 6.4×10^1	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
23. Culebra Fracture Retardation Factor for Uranium (dimensionless)	Piecewise Linear cdf	1 to 6.4×10^3	MEF-subjective percentiles (0, 25, 50, 75, 100) provided by principal investigator
24. Culebra Hydraulic Conductivity for Zone 1 (m/s)	Piecewise Linear cdf	2.7×10^{-6} to 5.5×10^{-5}	Subjective percentiles provided by principal investigator
25. Culebra Hydraulic Conductivity for Zone 2 (m/s)	Piecewise Linear cdf	9.9×10^{-9} to 4.3×10^{-8}	Subjective percentiles provided by principal investigator
26. Culebra Hydraulic Conductivity for Zone 3 (m/s)	Piecewise Linear cdf	1.3×10^{-7} to 3.2×10^{-7}	Subjective percentiles provided by principal investigator
27. Culebra Hydraulic Conductivity for Zone 4 (m/s)	Piecewise Linear cdf	3.5×10^{-8} to 1.2×10^{-7}	Subjective percentiles provided by principal investigator
28. Culebra Hydraulic Conductivity for Zone 5 (m/s)	Piecewise Linear cdf	4.0×10^{-6} to 4.8×10^{-6}	Subjective percentiles provided by principal investigator

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*Maximum Entropy Formalism; see Tierney, 1990 for additional explanation

Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS (continued)

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
29. Culebra Hydraulic Conductivity for Zone 7 (m/s)	Piecewise Linear cdf	1.6×10^{-5} to 2.0×10^{-4}	Subjective percentiles provided by principal investigator
30. Culebra Hydraulic Conductivity for Zone A (m/s)	Piecewise Linear cdf	1.6×10^{-4} to 1.0×10^{-3}	Subjective percentiles provided by principal investigator
31. Culebra Hydraulic Conductivity for Zone B (m/s)	Piecewise Linear cdf	1.6×10^{-5} to 1.3×10^{-4}	Subjective percentiles provided by principal investigator
32. Culebra Hydraulic Conductivity for Zone D (m/s)	Piecewise Linear cdf	3.3×10^{-5} to 5.2×10^{-5}	Subjective percentiles provided by principal investigator
33. Culebra Hydraulic Conductivity for Zone E (m/s)	Piecewise Linear cdf	1.6×10^{-7} to 1.3×10^{-6}	Subjective percentiles provided by principal investigator
34. Culebra Hydraulic Conductivity for Zone F (m/s)	Piecewise Linear cdf	2.6×10^{-6} to 1.6×10^{-5}	Subjective percentiles provided by principal investigator
35. Culebra Hydraulic Conductivity for Zone G (m/s)	Piecewise Linear cdf	1.3×10^{-8} to 1.6×10^{-7}	Subjective percentiles provided by principal investigator
36. Culebra Hydraulic Conductivity for Zone H (m/s)	Piecewise Linear cdf	3.3×10^{-7} to 4.1×10^{-5}	Subjective percentiles provided by principal investigator
37. Culebra Hydraulic Conductivity for Zone I (m/s)	Piecewise Linear cdf	6.5×10^{-10} to 1.0×10^{-9}	Subjective percentiles provided by principal investigator

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Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS (continued)

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
38. Culebra Hydraulic Conductivity for Zone J (m/s)	Piecewise Linear cdf	5.2×10^{-6} to 7.3×10^{-5}	Subjective percentiles provided by principal investigator
39. Culebra Hydraulic Conductivity for Zone K (m/s)	Piecewise Linear cdf	2.6×10^{-9} to 3.3×10^{-8}	Subjective percentiles provided by principal investigator
40. Number of Intrusions (dimensionless)	Histogram	1 to 13	Probabilities determined by sampling a Poisson distribution
41. Time of Intrusion 1 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
42. Time of Intrusion 2 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
43. Time of Intrusion 3 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
44. Time of Intrusion 4 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
45. Time of Intrusion 5 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
46. Time of Intrusion 6 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
47. Time of Intrusion 7 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
48. Time of Intrusion 8 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
49. Time of Intrusion 9 (seconds)	Uniform	3.156×10^{9} to 3.156×10^{11}	40 CFR Part 191, Subpart B
50. Room of Intrusion 1 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
51. Room of Intrusion 2 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
52. Room of Intrusion 3 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
53. Room of Intrusion 4 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a

Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-1. DISTRIBUTIONS OF SAMPLED QUANTITIES IN DECEMBER 1990 WIPP PERFORMANCE SIMULATIONS (concluded)

Quantity Name and Units	Type of Distribution	Range	Source or Basis for Distribution
54. Room of Intrusion 5 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
55. Room of Intrusion 6 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
56. Room of Intrusion 7 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
57. Room of Intrusion 8 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a
58. Room of Intrusion 9 (dimensionless)	Uniform	1 to 145	Rechard et al., 1990a

Sources: Tierney, 1990; Rechard et al., 1990a

TABLE C-2. SAMPLED VALUES FOR INTRUSION SCENARIOS E1, E2, AND E1E2

Parameters

x(1)	Salado capacitance (Pa^{-1})
x(2)	Salado permeability (m^2)
x(3)	Salado pressure (Pa)
x(4)	Solubility in room (all radionuclides) (kg/kg)
x(5)	Time (seconds) of first intrusion
x(6)	Brine pocket pressure (Pa)
x(7)	Borehole hydraulic conductivity (m/s)
x(8)	Borehole porosity (dimensionless)
x(9)	Brine pocket bulk volume (m^3)
x(10)	Culebra tortuosity (dimensionless)
x(11)	Culebra diffusion coefficient (all radionuclides) (m^2/s)
x(12)	Culebra fracture spacing (m)
x(13)	Culebra recharge factor (dimensionless)
x(14)	Culebra precipitation factor (dimensionless)
x(15)	Borehole cross-sectional area (m^2)
x(16)	Culebra matrix retardation factor for plutonium (dimensionless)
x(17)	Culebra matrix retardation factor for americium (dimensionless)
x(18)	Culebra matrix retardation factor for neptunium (dimensionless)
x(19)	Culebra matrix retardation factor for uranium (dimensionless)
x(20)	Culebra fracture retardation factor for plutonium (dimensionless)
x(21)	Culebra fracture retardation factor for americium (dimensionless)
x(22)	Culebra fracture retardation factor for neptunium (dimensionless)
x(23)	Culebra fracture retardation factor for uranium (dimensionless)
x(24)	Culebra hydraulic conductivity for zone 1 (m/s)
x(25)	Culebra hydraulic conductivity for zone 2 (m/s)
x(26)	Culebra hydraulic conductivity for zone 3 (m/s)
x(27)	Culebra hydraulic conductivity for zone 4 (m/s)
x(28)	Culebra hydraulic conductivity for zone 5 (m/s)
x(29)	Culebra hydraulic conductivity for zone 7 (m/s)

TABLE C-2a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2

RUN NO.	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)
1	5.711×10^{-11}	2.933×10^{-21}	1.090×10^{7}	1.476×10^{-5}	1.026×10^{11}	1.397×10^{7}
2	1.939×10^{-11}	4.500×10^{-21}	1.496×10^{7}	2.943×10^{-7}	6.249×10^{9}	8.397×10^{6}
3	1.205×10^{-11}	1.459×10^{-20}	8.317×10^{6}	4.963×10^{-9}	1.569×10^{11}	9.141×10^{6}
4	4.003×10^{-11}	2.884×10^{-21}	1.031×10^{7}	5.861×10^{-10}	2.360×10^{10}	7.092×10^{6}
5	3.096×10^{-11}	4.645×10^{-21}	1.139×10^{7}	4.725×10^{-6}	5.171×10^{10}	1.443×10^{7}
6	2.271×10^{-11}	2.546×10^{-20}	1.173×10^{7}	2.091×10^{-4}	6.102×10^{10}	1.356×10^{7}
7	4.266×10^{-11}	4.856×10^{-21}	9.675×10^{6}	5.673×10^{-8}	4.368×10^{10}	1.153×10^{7}
8	5.420×10^{-11}	6.496×10^{-21}	1.442×10^{7}	5.936×10^{-9}	3.040×10^{11}	1.252×10^{7}
9	3.406×10^{-11}	2.730×10^{-20}	1.005×10^{7}	1.624×10^{-8}	3.319×10^{10}	1.166×10^{7}
10	2.757×10^{-11}	1.893×10^{-20}	7.920×10^{6}	2.349×10^{-5}	3.839×10^{10}	1.290×10^{7}
11	2.384×10^{-11}	2.717×10^{-20}	8.176×10^{6}	1.968×10^{-5}	9.651×10^{10}	1.032×10^{7}
12	1.751×10^{-11}	8.877×10^{-22}	1.399×10^{7}	1.330×10^{-7}	5.408×10^{10}	1.703×10^{7}
13	3.624×10^{-11}	3.423×10^{-21}	1.276×10^{7}	2.749×10^{-10}	6.754×10^{10}	8.629×10^{6}
14	3.057×10^{-11}	2.540×10^{-21}	7.491×10^{6}	7.038×10^{-7}	2.351×10^{11}	1.328×10^{7}
15	4.660×10^{-11}	5.258×10^{-21}	1.254×10^{7}	7.157×10^{-8}	2.155×10^{10}	1.662×10^{7}
16	3.720×10^{-11}	1.755×10^{-21}	1.421×10^{7}	1.049×10^{-4}	3.614×10^{10}	7.624×10^{6}
17	1.863×10^{-11}	1.476×10^{-21}	9.587×10^{6}	2.512×10^{-6}	1.712×10^{10}	1.471×10^{7}
18	4.994×10^{-11}	4.422×10^{-21}	8.815×10^{6}	2.060×10^{-9}	8.900×10^{10}	1.373×10^{7}
19	2.587×10^{-11}	3.090×10^{-21}	9.005×10^{6}	1.272×10^{-9}	8.146×10^{10}	1.525×10^{7}
20	2.614×10^{-11}	3.574×10^{-21}	1.065×10^{7}	4.247×10^{-5}	1.190×10^{11}	9.391×10^{6}
21	4.191×10^{-11}	2.262×10^{-20}	1.404×10^{7}	8.879×10^{-6}	2.814×10^{10}	1.614×10^{7}
22	2.952×10^{-11}	1.989×10^{-21}	7.308×10^{6}	8.940×10^{-8}	2.007×10^{11}	1.672×10^{7}
23	3.182×10^{-11}	1.946×10^{-20}	1.470×10^{7}	2.670×10^{-8}	2.574×10^{11}	1.227×10^{7}
24	3.943×10^{-11}	1.021×10^{-21}	1.365×10^{7}	9.825×10^{-7}	1.596×10^{10}	1.482×10^{7}
25	7.619×10^{-11}	4.259×10^{-21}	7.040×10^{6}	4.742×10^{-7}	4.851×10^{10}	9.738×10^{6}
26	1.000×10^{-11}	5.736×10^{-21}	9.851×10^{6}	1.205×10^{-4}	7.760×10^{10}	1.084×10^{7}
27	2.051×10^{-11}	4.125×10^{-21}	8.728×10^{6}	1.194×10^{-8}	1.001×10^{10}	1.632×10^{7}
28	3.338×10^{-11}	2.399×10^{-21}	1.109×10^{7}	2.121×10^{-7}	1.739×10^{11}	1.720×10^{7}
29	5.226×10^{-11}	1.223×10^{-20}	1.281×10^{7}	5.321×10^{-5}	1.406×10^{11}	1.202×10^{7}
30	8.535×10^{-11}	2.350×10^{-21}	1.057×10^{7}	4.262×10^{-10}	4.394×10^{9}	1.543×10^{7}
31	6.270×10^{-11}	3.721×10^{-21}	1.198×10^{7}	1.542×10^{-6}	2.883×10^{10}	1.415×10^{7}
32	2.196×10^{-11}	5.612×10^{-22}	1.351×10^{7}	3.297×10^{-6}	1.832×10^{11}	1.012×10^{7}
33	4.502×10^{-11}	3.177×10^{-21}	8.507×10^{6}	8.323×10^{-5}	6.481×10^{10}	1.044×10^{7}
34	3.504×10^{-11}	2.113×10^{-21}	9.225×10^{6}	7.310×10^{-6}	7.114×10^{10}	1.307×10^{7}
35	2.175×10^{-11}	2.659×10^{-21}	7.772×10^{6}	7.967×10^{-9}	1.073×10^{11}	1.113×10^{7}
36	6.617×10^{-11}	3.804×10^{-22}	1.152×10^{7}	6.480×10^{-7}	1.464×10^{11}	8.821×10^{6}
37	1.620×10^{-11}	3.268×10^{-21}	1.320×10^{7}	9.298×10^{-10}	1.146×10^{11}	1.567×10^{7}
38	2.468×10^{-11}	1.727×10^{-20}	1.318×10^{7}	3.182×10^{-9}	2.106×10^{11}	1.586×10^{7}
39	2.796×10^{-11}	3.910×10^{-21}	1.211×10^{7}	3.040×10^{-8}	1.288×10^{11}	7.405×10^{6}
40	1.428×10^{-11}	9.771×10^{-21}	1.231×10^{7}	1.437×10^{-9}	1.146×10^{10}	7.869×10^{6}

TABLE C-2a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (continued)

RUN NO.	X(7)	X(8)	X(9)	X(10)	X(11)	X(12)
1	3.164×10^{-5}	0.384	1.115×10^{7}	3.112×10^{-2}	1.752×10^{-10}	6.33
2	4.858×10^{-4}	0.374	2.245×10^{6}	9.380×10^{-2}	3.767×10^{-10}	2.32
3	2.094×10^{-4}	0.287	9.393×10^{6}	3.505×10^{-2}	3.204×10^{-10}	1.26
4	2.728×10^{-4}	0.425	9.891×10^{6}	7.301×10^{-2}	2.390×10^{-10}	1.86
5	1.326×10^{-4}	0.458	1.916×10^{6}	8.930×10^{-2}	3.144×10^{-10}	4.59
6	4.458×10^{-4}	0.416	4.633×10^{6}	0.153	1.126×10^{-10}	0.435
7	1.228×10^{-4}	0.283	5.972×10^{6}	0.238	1.163×10^{-10}	5.08
8	3.508×10^{-4}	0.354	8.469×10^{6}	0.266	4.088×10^{-10}	1.55
9	2.463×10^{-5}	0.343	1.340×10^{7}	0.253	7.196×10^{-11}	0.925
10	9.029×10^{-4}	0.467	7.025×10^{6}	0.318	3.875×10^{-10}	2.95
11	2.345×10^{-3}	0.302	7.975×10^{6}	0.108	1.291×10^{-10}	1.41
12	1.130×10^{-4}	0.327	1.125×10^{7}	0.129	2.685×10^{-10}	0.862
13	1.088×10^{-3}	0.366	1.042×10^{7}	0.159	8.246×10^{-11}	1.14
14	6.506×10^{-4}	0.393	1.278×10^{7}	9.973×10^{-2}	2.604×10^{-10}	1.36
15	5.582×10^{-3}	0.264	6.698×10^{6}	4.659×10^{-2}	3.503×10^{-10}	2.14
16	3.019×10^{-4}	0.415	1.380×10^{7}	0.188	4.143×10^{-10}	1.96
17	2.442×10^{-4}	0.398	1.430×10^{6}	0.233	1.845×10^{-10}	1.03
18	5.204×10^{-4}	0.371	3.719×10^{5}	0.121	3.926×10^{-10}	0.588
19	8.061×10^{-4}	0.439	5.145×10^{6}	0.107	2.273×10^{-10}	1.80
20	6.674×10^{-5}	0.40	7.699×10^{6}	8.390×10^{-2}	3.723×10^{-10}	0.313
21	1.018×10^{-4}	0.436	8.123×10^{6}	9.597×10^{-2}	2.942×10^{-10}	0.981
22	1.639×10^{-3}	0.358	1.309×10^{7}	9.009×10^{-2}	3.414×10^{-10}	1.62
23	1.966×10^{-4}	0.386	9.498×10^{6}	0.291	4.236×10^{-10}	5.00
24	1.000×10^{-2}	0.332	3.770×10^{6}	9.841×10^{-2}	1.517×10^{-10}	2.73
25	1.704×10^{-4}	0.363	5.853×10^{6}	2.460×10^{-2}	3.552×10^{-10}	3.29
26	1.187×10^{-3}	0.319	1.186×10^{7}	0.135	2.538×10^{-10}	3.88
27	1.134×10^{-5}	0.311	8.762×10^{6}	0.261	3.281×10^{-10}	5.71
28	1.310×10^{-3}	0.356	9.869×10^{5}	0.152	3.013×10^{-10}	5.33
29	3.937×10^{-4}	0.337	1.275×10^{6}	9.704×10^{-2}	5.587×10^{-11}	4.26
30	1.602×10^{-4}	0.391	1.050×10^{7}	9.217×10^{-2}	1.945×10^{-10}	0.648
31	2.765×10^{-3}	0.429	1.221×10^{7}	0.139	1.397×10^{-10}	5.86
32	5.027×10^{-5}	0.409	5.386×10^{6}	3.793×10^{-2}	9.504×10^{-11}	3.14
33	4.539×10^{-5}	0.345	2.794×10^{5}	9.253×10^{-2}	2.783×10^{-10}	0.739
34	5.651×10^{-4}	0.381	1.226×10^{7}	8.128×10^{-2}	9.637×10^{-11}	6.03
35	2.310×10^{-4}	0.50	3.918×10^{6}	0.123	1.719×10^{-10}	6.80
36	7.986×10^{-5}	0.32	2.937×10^{6}	0.299	2.102×10^{-10}	3.73
37	7.739×10^{-5}	0.377	2.738×10^{6}	0.21	1.620×10^{-10}	6.65
38	3.304×10^{-4}	0.444	6.448×10^{6}	0.181	6.331×10^{-11}	0.402
39	2.095×10^{-3}	0.404	3.444×10^{6}	0.125	2.483×10^{-10}	1.69
40	7.013×10^{-4}	0.347	4.272×10^{6}	0.146	2.184×10^{-10}	4.21

TABLE C-2a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (continued)

RUN NO.	X(13)	X(14)	X(15)	X(16)	X(17)	X(18)
1	0.162	0.522	3.142×10^{-2}	7.301×10^{3}	5.121×10^{3}	117.
2	0.359	5.783×10^{-2}	3.142×10^{-2}	1.295×10^{3}	287.	8.03
3	0.681	1.96	7.604×10^{-2}	4.738×10^{3}	2.579×10^{3}	9.63
4	1.8	0.992	3.142×10^{-2}	2.451×10^{3}	2.099×10^{3}	81.4
5	1.9	1.37	6.131×10^{-2}	1.417×10^{3}	1.518×10^{3}	15.9
6	1.18	1.76	4.694×10^{-2}	1.215×10^{4}	1.597×10^{3}	42.5
7	0.831	0.131	7.604×10^{-2}	1.509×10^{4}	549.	8.47
8	1.1	0.892	0.153	1.152×10^{3}	1.554×10^{3}	11.8
9	1.66	1.07	3.142×10^{-2}	85.9	4.389×10^{3}	13.5
10	0.955	0.743	2.141×10^{-2}	1.130×10^{4}	3.034×10^{3}	56.4
11	1.32	0.212	3.142×10^{-2}	512.	1.842×10^{3}	101.
12	1.1	0.669	3.142×10^{-2}	1.371×10^{4}	2.235×10^{3}	135.
13	1.24	1.86	3.142×10^{-2}	1.335×10^{3}	2.899×10^{3}	6.89
14	0.517	0.178	7.604×10^{-2}	928.	1.527×10^{3}	1.0
15	1.81	0.589	3.142×10^{-2}	164.	2.373×10^{3}	4.42
16	0.101	1.58	3.142×10^{-2}	354.	3.323×10^{3}	14.3
17	0.643	0.275	0.114	958.	1.903×10^{3}	11.2
18	0.747	1.52	3.142×10^{-2}	6.782×10^{3}	4.598×10^{3}	1.0
19	0.794	3.825×10^{-2}	3.879×10^{-2}	1.369×10^{3}	4.190×10^{3}	1.0
20	1.98	1.46	4.573×10^{-2}	378.	1.224×10^{3}	1.0
21	0.206	1.63	7.760×10^{-2}	328.	1.570×10^{3}	2.42
22	5.058×10^{-2}	1.23	1.533×10^{-2}	1.083×10^{3}	33.8	12.7
23	1.7	0.614	2.309×10^{-2}	1.255×10^{3}	1.548×10^{3}	1.0
24	1.04	0.796	3.879×10^{-2}	57.7	4.833×10^{3}	13.9
25	1.42	0.488	3.142×10^{-2}	118.	1.539×10^{3}	23.8
26	1.87	1.28	1.979×10^{-2}	1.485×10^{3}	2.835×10^{3}	1.0
27	0.941	0.912	3.142×10^{-2}	31.3	833.	1.89
28	1.56	1.94	3.142×10^{-2}	681.	1.563×10^{3}	145.
29	0.565	1.42	3.142×10^{-2}	745.	747.	11.8
30	1.46	1.17	2.309×10^{-2}	4.187×10^{3}	387.	15.
31	1.54	1.7	2.309×10^{-2}	9.811×10^{3}	935.	1.0
32	1.6	0.415	2.629×10^{-2}	257.	1.510×10^{3}	10.1
33	0.318	1.12	1.533×10^{-2}	1.405×10^{3}	3.954×10^{3}	1.0
34	1.29	0.802	0.155	1.205×10^{3}	3.594×10^{3}	1.0
35	0.486	1.84	3.449×10^{-2}	295.	1.706×10^{3}	54.3
36	0.263	1.34	4.573×10^{-2}	1.268×10^{3}	2.607×10^{3}	1.0
37	1.36	1.03	1.979×10^{-2}	1.450×10^{3}	5.491×10^{3}	5.86
38	0.422	0.308	1.979×10^{-2}	208.	1.585×10^{3}	4.7
39	0.881	0.385	2.309×10^{-2}	860.	1.499×10^{3}	94.3
40	3.417×10^{-2}	1.72	3.661×10^{-2}	546.	1.182×10^{3}	3.13

TABLE C-2a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (continued)

RUN NO.	X(19)	X(20)	X(21)	X(22)	X(23)	X(24)
1	10.1	2.005×10^{4}	278.	17.	9.32	1.042×10^{-5}
2	15.5	1.274×10^{4}	91.2	1.93	12.4	2.320×10^{-5}
3	30.2	121.	606.	1.67	19.5	2.046×10^{-5}
4	5.22	170.	309.	14.4	56.8	4.852×10^{-5}
5	7.61	227.	4.943×10^{3}	11.4	15.8	3.684×10^{-5}
6	1.0	4.988×10^{4}	501.	33.9	47.	4.814×10^{-6}
7	6.87	90.	4.139×10^{3}	46.2	1.55	3.671×10^{-5}
8	1.0	193.	132.	1.44	21.6	3.050×10^{-6}
9	35.6	76.4	552.	3.72	1.09	1.100×10^{-5}
10	1.0	333.	122.	2.54	1.34	4.989×10^{-5}
11	44.4	1.453×10^{3}	337.	2.05	5.9	1.218×10^{-5}
12	80.5	308.	526.	1.29	31.8	4.317×10^{-6}
13	10.6	259.	260.	63.	20.	3.633×10^{-5}
14	21.3	1.066×10^{3}	66.2	8.39	42.	5.268×10^{-5}
15	96.5	108.	433.	21.6	13.4	9.815×10^{-6}
16	14.9	54.9	4.567×10^{3}	25.	40.4	1.153×10^{-5}
17	1.04	9.61	268.	7.3	6.93	1.622×10^{-5}
18	11.3	2.835×10^{3}	2.725×10^{3}	2.1	10.8	4.012×10^{-5}
19	90.8	294.	1.986×10^{3}	60.2	25.9	2.935×10^{-6}
20	13.7	3.868×10^{4}	354.	19.5	2.89	1.063×10^{-5}
21	13.6	98.	23.5	55.3	1.98	4.469×10^{-5}
22	1.0	2.281×10^{3}	591.	41.	3.47	3.602×10^{-5}
23	1.0	44.9	877.	32.6	2.13	3.094×10^{-5}
24	1.0	2.549×10^{3}	1.879×10^{3}	1.84	8.11	4.268×10^{-5}
25	12.8	364.	181.	14.	63.4	8.540×10^{-6}
26	1.0	253.	156.	23.9	5.32	1.169×10^{-5}
27	3.78	3.098×10^{4}	2.944×10^{3}	28.9	35.5	3.606×10^{-5}
28	55.	495.	241.	42.9	17.	1.018×10^{-5}
29	14.8	25.1	574.	9.82	49.	2.973×10^{-5}
30	1.0	1.787×10^{3}	214.	12.7	1.71	5.845×10^{-6}
31	68.6	2.079×10^{3}	323.	1.06	23.4	7.475×10^{-6}
32	9.21	650.	300.	15.3	1.92	8.816×10^{-6}
33	1.0	32.8	374.	17.9	24.8	3.507×10^{-6}
34	1.0	2.608×10^{4}	464.	22.6	18.2	7.005×10^{-6}
35	8.82	145.	385.	1.58	1.41	3.585×10^{-6}
36	104.	4.095×10^{4}	425.	4.66	1.13	3.698×10^{-5}
37	6.0	1.079×10^{4}	46.7	20.1	32.9	3.662×10^{-5}
38	2.24	5.744×10^{3}	3.701×10^{3}	1.18	26.9	3.645×10^{-5}
39	12.2	3.308×10^{4}	1.125×10^{3}	51.	1.8	4.854×10^{-6}
40	2.94	1.317×10^{3}	367.	6.9	14.6	3.961×10^{-6}

TABLE C-2a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (concluded)

RUN NO.	X(25)	X(26)	X(27)	X(28)	X(29)
1	2.816×10^{-8}	1.831×10^{-7}	8.296×10^{-8}	4.438×10^{-6}	1.556×10^{-4}
2	1.338×10^{-8}	1.367×10^{-7}	5.326×10^{-8}	4.164×10^{-6}	1.685×10^{-5}
3	3.747×10^{-8}	1.326×10^{-7}	4.659×10^{-8}	4.703×10^{-6}	9.794×10^{-5}
4	2.930×10^{-8}	2.681×10^{-7}	8.244×10^{-8}	4.482×10^{-6}	1.829×10^{-4}
5	1.052×10^{-8}	2.799×10^{-7}	5.877×10^{-8}	4.071×10^{-6}	1.048×10^{-4}
6	2.707×10^{-8}	2.865×10^{-7}	1.011×10^{-7}	4.406×10^{-6}	1.305×10^{-4}
7	1.876×10^{-8}	1.391×10^{-7}	8.318×10^{-8}	4.281×10^{-6}	4.019×10^{-5}
8	1.480×10^{-8}	2.359×10^{-7}	6.622×10^{-8}	4.308×10^{-6}	5.367×10^{-5}
9	1.355×10^{-8}	1.347×10^{-7}	8.232×10^{-8}	4.241×10^{-6}	1.689×10^{-4}
10	3.805×10^{-8}	2.979×10^{-7}	5.267×10^{-8}	4.763×10^{-6}	1.114×10^{-4}
11	4.300×10^{-8}	2.949×10^{-7}	3.612×10^{-8}	4.150×10^{-6}	2.427×10^{-5}
12	3.129×10^{-8}	2.846×10^{-7}	5.978×10^{-8}	4.381×10^{-6}	1.740×10^{-4}
13	1.152×10^{-8}	3.126×10^{-7}	4.801×10^{-8}	4.447×10^{-6}	4.737×10^{-5}
14	1.286×10^{-8}	2.419×10^{-7}	7.724×10^{-8}	4.017×10^{-6}	1.921×10^{-4}
15	1.029×10^{-8}	3.068×10^{-7}	1.039×10^{-7}	4.611×10^{-6}	1.226×10^{-4}
16	3.556×10^{-8}	1.795×10^{-7}	8.165×10^{-8}	4.231×10^{-6}	3.550×10^{-5}
17	1.390×10^{-8}	1.388×10^{-7}	8.823×10^{-8}	4.748×10^{-6}	1.765×10^{-4}
18	4.235×10^{-8}	1.557×10^{-7}	1.170×10^{-7}	4.060×10^{-6}	1.461×10^{-4}
19	4.220×10^{-8}	2.479×10^{-7}	5.429×10^{-8}	4.585×10^{-6}	5.768×10^{-5}
20	3.184×10^{-8}	1.938×10^{-7}	8.645×10^{-8}	4.789×10^{-6}	2.911×10^{-5}
21	3.962×10^{-8}	1.646×10^{-7}	5.676×10^{-8}	4.181×10^{-6}	1.356×10^{-4}
22	1.254×10^{-8}	2.178×10^{-7}	1.079×10^{-7}	4.739×10^{-6}	5.037×10^{-5}
23	4.094×10^{-8}	2.520×10^{-7}	5.368×10^{-8}	4.503×10^{-6}	1.900×10^{-4}
24	3.382×10^{-8}	2.208×10^{-7}	7.335×10^{-8}	4.640×10^{-6}	9.370×10^{-5}
25	3.024×10^{-8}	1.377×10^{-7}	9.150×10^{-8}	4.570×10^{-6}	6.587×10^{-5}
26	3.486×10^{-8}	1.988×10^{-7}	1.134×10^{-7}	4.039×10^{-6}	7.206×10^{-5}
27	3.754×10^{-8}	2.724×10^{-7}	4.388×10^{-8}	4.268×10^{-6}	1.819×10^{-4}
28	3.690×10^{-8}	1.315×10^{-7}	5.098×10^{-8}	4.101×10^{-6}	1.662×10^{-4}
29	4.173×10^{-8}	2.280×10^{-7}	8.377×10^{-8}	4.679×10^{-6}	8.367×10^{-5}
30	4.268×10^{-8}	2.053×10^{-7}	7.410×10^{-8}	4.126×10^{-6}	7.545×10^{-5}
31	2.529×10^{-8}	1.330×10^{-7}	5.231×10^{-8}	4.641×10^{-6}	1.853×10^{-4}
32	4.021×10^{-8}	2.631×10^{-7}	1.096×10^{-7}	4.353×10^{-6}	1.725×10^{-4}
33	1.103×10^{-8}	2.321×10^{-7}	4.054×10^{-8}	4.210×10^{-6}	1.533×10^{-4}
34	3.293×10^{-8}	1.470×10^{-7}	5.310×10^{-8}	4.469×10^{-6}	1.619×10^{-4}
35	1.205×10^{-8}	2.555×10^{-7}	9.571×10^{-8}	4.090×10^{-6}	2.283×10^{-5}
36	2.156×10^{-8}	3.182×10^{-7}	6.984×10^{-8}	4.551×10^{-6}	1.190×10^{-4}
37	2.421×10^{-8}	1.352×10^{-7}	8.397×10^{-8}	4.699×10^{-6}	4.263×10^{-5}
38	1.315×10^{-8}	1.618×10^{-7}	6.217×10^{-8}	4.335×10^{-6}	6.338×10^{-5}
39	1.233×10^{-8}	1.304×10^{-7}	6.361×10^{-8}	4.370×10^{-6}	1.992×10^{-4}
40	3.873×10^{-8}	3.039×10^{-7}	9.671×10^{-8}	4.522×10^{-6}	1.947×10^{-4}

TABLE C-2b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2

RUN NO.	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)
1	36.	14.	20.	32.	26.	26.	3.	23.
2	7.	25.	40.	21.	2.	5.	25.	20.
3	2.	33.	7.	9.	33.	8.	16.	3.
4	28.	13.	17.	3.	8.	1.	19.	33.
5	20.	26.	22.	29.	16.	28.	12.	38.
6	11.	38.	24.	40.	18.	24.	24.	32.
7	30.	27.	14.	16.	14.	16.	11.	2.
8	35.	30.	38.	10.	40.	20.	22.	14.
9	23.	40.	16.	13.	11.	17.	2.	11.
10	16.	35.	5.	34.	13.	21.	31.	39.
11	12.	39.	6.	33.	25.	12.	37.	4.
12	5.	3.	35.	19.	17.	39.	10.	8.
13	25.	18.	29.	1.	20.	6.	32.	18.
14	19.	11.	3.	24.	38.	23.	28.	26.
15	32.	28.	28.	17.	7.	37.	39.	1.
16	26.	6.	37.	38.	12.	3.	20.	31.
17	6.	5.	13.	27.	6.	29.	18.	27.
18	33.	24.	10.	7.	24.	25.	26.	19.
19	14.	15.	11.	5.	23.	31.	30.	36.
20	15.	19.	19.	35.	29.	9.	6.	28.
21	29.	37.	36.	31.	9.	35.	9.	35.
22	18.	7.	2.	18.	36.	38.	35.	16.
23	21	36.	39.	14.	39.	19.	15.	24.
24	27.	4.	34.	25.	5.	30.	40.	9.
25	39.	23.	1.	22.	15.	10.	14.	17.
26	1.	29.	15.	39.	22.	14.	33.	6.
27	8.	22.	9.	12.	3.	36.	1.	5.
28	22.	10.	21.	20.	34.	40.	34.	15.
29	34.	32.	30.	36.	31.	18.	23.	10.
30	40.	9.	18.	2.	1.	32.	13.	25.
31	37.	20.	25.	26.	10.	27.	38.	34.
32	10.	2.	33.	28.	35.	11.	5.	30.
33	31.	16.	8.	37.	19.	13.	4.	12.
34	24.	8.	12.	30.	21.	22.	27.	22.
35	9.	12.	4.	11.	27.	15.	17.	40.
36	38.	1.	23.	23.	32.	7.	8.	7.
37	4.	17.	32.	4.	28.	33.	7.	21.
38	13.	34.	31.	8.	37.	34.	21.	37.
39	17.	21.	26.	15.	30.	2.	36.	29.
40	3.	31.	27.	6.	4.	4.	29.	13.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-2a is the smallest value sampled for that parameter.

TABLE C-2b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (continued)

RUN NO.	X(9)	X(10)	X(11)	X(12)	X(13)	X(14)	X(15)	X(16)
1	32.	2.	14.	38.	4.	11.	19.	35.
2	7.	13.	35.	22.	8.	2.	19.	24.
3	27.	3.	29.	12.	14.	40.	35.	33.
4	29.	6.	20.	19.	36.	20.	19.	31.
5	6.	9.	28.	31.	39.	28.	33.	28.
6	14.	28.	7.	3.	24.	36.	32.	38.
7	18.	34.	8.	33.	17.	3.	35.	40.
8	25.	37.	38.	15.	22.	18.	39.	20.
9	39.	35.	3.	8.	34.	22.	19.	3.
10	21.	40.	36.	24.	20.	15.	6.	37.
11	23.	19.	9.	14.	27.	5.	19.	12.
12	33.	23.	24.	7.	23.	14.	19.	39.
13	30.	29.	4.	11.	25.	38.	19.	25.
14	37.	17.	23.	13.	11.	4.	35.	17.
15	20.	5.	32.	21.	37.	12.	19.	5.
16	40.	31.	39.	20.	3.	32.	19.	10.
17	5.	33.	15.	10.	13.	6.	38.	18.
18	2.	20.	37.	4.	15.	31.	18.	34.
19	15.	18.	19.	18.	16.	1.	29.	26.
20	22.	8.	34.	1.	40.	30.	31.	11.
21	24.	14.	26.	9.	5.	33.	37.	9.
22	38.	10.	31.	16.	2.	25.	2.	19.
23	28.	38.	40.	32.	35.	13.	9.	22.
24	11.	16.	11.	23.	21.	16.	29.	2.
25	17.	1.	33.	26.	29.	10.	19.	4.
26	34.	24.	22.	28.	38.	26.	4.	30.
27	26.	36.	30.	35.	19.	19.	19.	1.
28	3.	27.	27.	34.	32.	39.	19.	14.
29	4.	15.	1.	30.	12.	29.	19.	15.
30	31.	11.	16.	5.	30.	24.	9.	32.
31	35.	25.	10.	36.	31.	34.	9.	36.
32	16.	4.	5.	25.	33.	9.	11.	7.
33	1.	12.	25.	6.	7.	23.	2.	27.
34	36.	7.	6.	37.	26.	17.	40.	21.
35	12.	21.	13.	40.	10.	37.	26.	8.
36	9.	39.	17.	27.	6.	27.	31.	23.
37	8.	32.	12.	39.	28.	21.	4.	29.
38	19.	30.	2.	2.	9.	7.	4.	6.
39	10.	22.	21.	17.	18.	8.	9.	16.
40	13.	26.	18.	29.	1.	35.	27.	13.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-2a is the smallest value sampled for that parameter.

TABLE C-2b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (continued)

RUN NO.	X(17)	X(18)	X(19)	X(20)	X(21)	X(22)	X(23)	X(24)
1	39.	38.	21.	34.	13.	23.	17.	16.
2	2.	18.	30.	33.	4.	8.	19.	24.
3	27.	20.	32.	10.	30.	6.	25.	23.
4	24.	35.	15.	12.	15.	21.	39.	38.
5	12.	30.	18.	14.	40.	18.	22.	33.
6	20.	32.	6.	40.	25.	33.	36.	7.
7	4.	19.	17.	7.	38.	36.	5.	32.
8	16.	23.	6.	13.	6.	4.	27.	2.
9	36.	26.	33.	6.	27.	12.	1.	18.
10	31.	34.	6.	19.	5.	11.	3.	39.
11	22.	37.	34.	25.	17.	9.	14.	21.
12	25.	39.	37.	18.	26.	3.	32.	6.
13	30.	17.	22.	16.	11.	40.	26.	29.
14	13.	6.	31.	23.	3.	16.	35.	40.
15	26.	14.	39.	9.	23.	27.	20.	14.
16	32.	28.	29.	5.	39.	30.	34.	19.
17	23.	22.	11.	1.	12.	15.	15.	22.
18	37.	6.	23.	30.	35.	10.	18.	35.
19	35.	6.	38.	17.	34.	39.	30.	1.
20	9.	6.	27.	38.	18.	25.	11.	17.
21	18.	12.	26.	8.	1.	38.	9.	37.
22	1.	25.	6.	28.	29.	34.	12.	27.
23	15.	6.	6.	4.	31.	32.	10.	26.
24	38.	27.	6.	29.	33.	7.	16.	36.
25	14.	31.	25.	20.	8.	20.	40.	12.
26	29.	6.	6.	15.	7.	29.	13.	20.
27	6.	11.	14.	36.	36.	31.	33.	28.
28	17.	40.	35.	21.	10.	35.	23.	15.
29	5.	24.	28.	2.	28.	17.	37.	25.
30	3.	29.	6.	26.	9.	19.	6.	9.
31	7.	6.	36.	27.	16.	1.	28.	11.
32	11.	21.	20.	22.	14.	22.	8.	13.
33	34.	6.	6.	3.	20.	24.	29.	3.
34	33.	6.	6.	35.	24.	28.	24.	10.
35	21.	33.	19.	11.	21.	5.	4.	4.
36	28.	6.	40.	39.	22.	13.	2.	34.
37	40.	16.	16.	32.	2.	26.	38.	31.
38	19.	15.	12.	31.	37.	2.	31.	30.
39	10.	36.	24.	37.	32.	37.	7.	8.
40	8.	13.	13.	24.	19.	14.	21.	5.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-2a is the smallest value sampled for that parameter.

TABLE C-2b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR SCENARIOS E1, E2, AND E1E2 (concluded)

RUN NO.	X(25)	X(26)	X(27)	X(28)	X(29)
1	19.	16.	26.	22.	27.
2	10.	7.	10.	9.	1.
3	29.	3.	4.	36.	18.
4	20.	30.	25.	25.	35.
5	2.	32.	14.	4.	19.
6	18.	34.	35.	21.	23.
7	14.	10.	27.	15.	6.
8	13.	24.	18.	16.	10.
9	11.	5.	24.	13.	30.
10	31.	36.	8.	39.	20.
11	40.	35.	1.	8.	3.
12	22.	33.	15.	20.	32.
13	4.	39.	5.	23.	8.
14	8.	25.	22.	1.	38.
15	1.	38.	36.	31.	22.
16	27.	15.	23.	12.	5.
17	12.	9.	31.	38.	33.
18	38.	12.	40.	3.	25.
19	37.	26.	12.	30.	11.
20	23.	17.	30.	40.	4.
21	33.	14.	13.	10.	24.
22	7.	20.	37.	37.	9.
23	35.	27.	11.	26.	37.
24	25.	21.	20.	32.	17.
25	21.	8.	32.	29.	13.
26	26.	18.	39.	2.	14.
27	30.	31.	3.	14.	34.
28	28.	2.	6.	6.	29.
29	36.	22.	28.	34.	16.
30	39.	19.	21.	7.	15.
31	17.	4.	7.	33.	36.
32	34.	29.	38.	18.	31.
33	3.	23.	2.	11.	26.
34	24.	11.	9.	24.	28.
35	5.	28.	33.	5.	2.
36	15.	40.	19.	28.	21.
37	16.	6.	29.	35.	7.
38	9.	13.	16.	17.	12.
39	6.	1.	17.	19.	40.
40	32.	37.	34.	27.	39.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-2a is the smallest value sampled for that parameter.

TABLE C-3. SAMPLED VALUES FOR MULTIPLE INTRUSION SCENARIOS

Parameters

x(1)	Salado capacitance (Pa^{-1})
x(2)	Salado permeability (m^2)
x(3)	Salado pressure (Pa)
x(4)	Solubility in room (all radionuclides) (kg/kg)
x(5)	Brine pocket pressure (Pa)
x(6)	Borehole hydraulic conductivity (m/s)
x(7)	Borehole porosity (dimensionless)
x(8)	Brine pocket bulk volume (m^3)
x(9)	Culebra tortuosity (dimensionless)
x(10)	Culebra diffusion coefficient (all radionuclides) (m^2/s)
x(11)	Culebra fracture spacing (m)
x(12)	Culebra recharge factor (dimensionless)
x(13)	Culebra precipitation factor (dimensionless)
x(14)	Borehole cross-sectional area (m^2)
x(15)	Culebra matrix retardation factor for plutonium (dimensionless)
x(16)	Culebra matrix retardation factor for americium (dimensionless)
x(17)	Culebra matrix retardation factor for neptunium (dimensionless)
x(18)	Culebra matrix retardation factor for uranium (dimensionless)
x(19)	Culebra fracture retardation factor for plutonium (dimensionless)
x(20)	Culebra fracture retardation factor for americium (dimensionless)
x(21)	Culebra fracture retardation factor for neptunium (dimensionless)
x(22)	Culebra fracture retardation factor for uranium (dimensionless)
x(23)	Culebra hydraulic conductivity for zone A (m/s)
x(24)	Culebra hydraulic conductivity for zone B (m/s)
x(25)	Culebra hydraulic conductivity for zone D (m/s)
x(26)	Culebra hydraulic conductivity for zone E (m/s)
x(27)	Culebra hydraulic conductivity for zone F (m/s)
x(28)	Culebra hydraulic conductivity for zone G (m/s)
x(29)	Culebra hydraulic conductivity for zone H (m/s)
x(30)	Culebra hydraulic conductivity for zone I (m/s)
x(31)	Culebra hydraulic conductivity for zone J (m/s)
x(32)	Culebra hydraulic conductivity for zone K (m/s)
x(33)	number of intrusions (dimensionless)
x(34)	time of intrusion 1 (seconds)
x(35)	time of intrusion 2 (seconds)
x(36)	time of intrusion 3 (seconds)
x(37)	time of intrusion 4 (seconds)
x(38)	time of intrusion 5 (seconds)
x(39)	time of intrusion 6 (seconds)
x(40)	time of intrusion 7 (seconds)

x(41)	time of intrusion 8 (seconds)
x(42)	time of intrusion 9 (seconds)
x(43)	room of intrusion 1 (dimensionless)
x(44)	room of intrusion 2 (dimensionless)
x(45)	room of intrusion 3 (dimensionless)
x(46)	room of intrusion 4 (dimensionless)
x(47)	room of intrusion 5 (dimensionless)
x(48)	room of intrusion 6 (dimensionless)
x(49)	room of intrusion 7 (dimensionless)
x(50)	room of intrusion 8 (dimensionless)
x(51)	room of intrusion 9 (dimensionless)

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO

RUN NO.	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)
1	2.961×10^{-11}	3.487×10^{-21}	7.646×10^{6}	7.659×10^{-7}	1.572×10^{7}	5.006×10^{-4}
2	4.503×10^{-11}	4.412×10^{-21}	1.354×10^{7}	7.368×10^{-9}	1.480×10^{7}	2.786×10^{-4}
3	1.984×10^{-11}	1.315×10^{-21}	1.132×10^{7}	3.819×10^{-7}	1.503×10^{7}	5.346×10^{-4}
4	1.456×10^{-11}	2.947×10^{-21}	1.329×10^{7}	6.238×10^{-6}	1.195×10^{7}	1.479×10^{-3}
5	4.626×10^{-11}	2.178×10^{-21}	9.358×10^{6}	1.207×10^{-7}	1.543×10^{7}	1.623×10^{-4}
6	4.251×10^{-11}	1.085×10^{-21}	1.426×10^{7}	6.400×10^{-7}	1.279×10^{7}	1.203×10^{-4}
7	7.180×10^{-11}	4.284×10^{-21}	1.060×10^{7}	3.213×10^{-7}	1.684×10^{7}	2.137×10^{-5}
8	2.843×10^{-11}	3.079×10^{-21}	1.164×10^{7}	1.602×10^{-5}	1.334×10^{7}	1.522×10^{-4}
9	2.322×10^{-11}	3.605×10^{-21}	9.822×10^{6}	4.790×10^{-8}	1.247×10^{7}	1.442×10^{-4}
10	3.381×10^{-11}	1.869×10^{-20}	1.465×10^{7}	1.865×10^{-9}	1.180×10^{7}	3.691×10^{-4}
11	3.154×10^{-11}	2.595×10^{-21}	1.144×10^{7}	1.397×10^{-6}	1.303×10^{7}	4.507×10^{-5}
12	2.610×10^{-11}	2.692×10^{-21}	1.206×10^{7}	1.720×10^{-4}	1.529×10^{7}	2.525×10^{-5}
13	1.374×10^{-11}	3.792×10^{-21}	1.035×10^{7}	6.589×10^{-8}	1.227×10^{7}	2.958×10^{-4}
14	4.157×10^{-11}	1.191×10^{-20}	9.186×10^{6}	3.942×10^{-10}	1.618×10^{7}	9.779×10^{-5}
15	2.830×10^{-11}	1.498×10^{-20}	1.299×10^{7}	9.837×10^{-9}	1.387×10^{7}	4.131×10^{-5}
16	5.591×10^{-11}	2.676×10^{-20}	1.119×10^{7}	2.199×10^{-7}	1.707×10^{7}	1.326×10^{-3}
17	1.930×10^{-11}	2.361×10^{-20}	1.498×10^{7}	8.764×10^{-8}	1.111×10^{7}	6.961×10^{-4}
18	1.778×10^{-11}	4.065×10^{-21}	1.265×10^{7}	2.140×10^{-5}	1.698×10^{7}	9.132×10^{-5}
19	1.249×10^{-11}	2.498×10^{-21}	8.706×10^{6}	1.285×10^{-5}	1.402×10^{7}	2.142×10^{-3}
20	1.600×10^{-11}	3.721×10^{-21}	8.371×10^{6}	4.246×10^{-9}	1.153×10^{7}	1.290×10^{-4}
21	2.435×10^{-11}	1.133×10^{-21}	1.469×10^{7}	4.590×10^{-10}	1.718×10^{7}	6.054×10^{-4}
22	3.642×10^{-11}	2.298×10^{-21}	8.238×10^{6}	6.082×10^{-9}	1.672×10^{7}	4.137×10^{-4}
23	3.065×10^{-11}	4.429×10^{-21}	1.280×10^{7}	5.107×10^{-9}	1.738×10^{7}	1.143×10^{-4}
24	1.704×10^{-11}	2.017×10^{-21}	1.004×10^{7}	1.831×10^{-7}	1.609×10^{7}	1.000×10^{-5}
25	1.870×10^{-11}	2.220×10^{-21}	1.324×10^{7}	2.890×10^{-9}	1.394×10^{7}	3.105×10^{-3}
26	4.724×10^{-11}	1.679×10^{-20}	1.479×10^{7}	9.818×10^{-8}	1.442×10^{7}	1.557×10^{-3}
27	3.990×10^{-11}	3.047×10^{-21}	1.435×10^{7}	3.415×10^{-6}	1.599×10^{7}	1.064×10^{-4}
28	3.292×10^{-11}	3.238×10^{-21}	1.179×10^{7}	5.057×10^{-7}	1.228×10^{7}	2.467×10^{-4}
29	3.520×10^{-11}	1.427×10^{-22}	8.546×10^{6}	5.338×10^{-10}	1.367×10^{7}	1.140×10^{-3}
30	8.265×10^{-11}	4.181×10^{-21}	9.092×10^{6}	2.478×10^{-9}	1.473×10^{7}	6.596×10^{-5}
31	7.467×10^{-11}	3.521×10^{-21}	1.009×10^{7}	1.466×10^{-6}	1.272×10^{7}	7.828×10^{-5}
32	3.765×10^{-11}	4.660×10^{-21}	8.745×10^{6}	1.521×10^{-8}	1.246×10^{7}	1.896×10^{-3}
33	1.062×10^{-11}	4.744×10^{-21}	1.071×10^{7}	1.408×10^{-8}	1.284×10^{7}	5.795×10^{-5}
34	5.448×10^{-11}	2.384×10^{-21}	1.154×10^{7}	4.035×10^{-8}	1.561×10^{7}	8.670×10^{-3}
35	4.883×10^{-11}	2.547×10^{-21}	7.961×10^{6}	1.101×10^{-6}	1.105×10^{7}	3.227×10^{-4}
36	3.011×10^{-11}	1.372×10^{-21}	1.229×10^{7}	5.366×10^{-8}	1.316×10^{7}	1.565×10^{-5}
37	4.343×10^{-11}	2.469×10^{-22}	1.084×10^{7}	3.183×10^{-5}	1.488×10^{7}	7.399×10^{-3}
38	1.627×10^{-11}	7.854×10^{-21}	7.817×10^{6}	2.938×10^{-10}	1.625×10^{7}	1.022×10^{-3}
39	2.489×10^{-11}	1.572×10^{-21}	7.245×10^{6}	9.509×10^{-6}	1.579×10^{7}	4.830×10^{-4}
40	2.785×10^{-11}	1.987×10^{-21}	7.569×10^{6}	4.375×10^{-6}	1.415×10^{7}	1.964×10^{-4}
41	2.572×10^{-11}	2.729×10^{-21}	1.255×10^{7}	6.837×10^{-5}	1.382×10^{7}	8.878×10^{-5}
42	2.704×10^{-11}	6.677×10^{-22}	1.379×10^{7}	3.674×10^{-5}	1.359×10^{7}	3.120×10^{-4}
43	3.881×10^{-11}	3.150×10^{-21}	1.446×10^{7}	3.223×10^{-9}	1.343×10^{7}	1.892×10^{-4}
44	1.000×10^{-10}	3.950×10^{-21}	9.946×10^{6}	1.501×10^{-9}	1.210×10^{7}	9.014×10^{-4}
45	2.519×10^{-11}	1.741×10^{-21}	1.349×10^{7}	8.475×10^{-5}	1.656×10^{7}	4.516×10^{-4}
46	3.439×10^{-11}	4.078×10^{-21}	1.395×10^{7}	1.378×10^{-4}	1.727×10^{7}	1.856×10^{-3}
47	2.162×10^{-11}	1.387×10^{-20}	1.284×10^{7}	9.536×10^{-7}	1.534×10^{7}	2.455×10^{-3}
48	2.245×10^{-11}	5.236×10^{-22}	1.364×10^{7}	2.883×10^{-8}	1.647×10^{7}	3.854×10^{-4}
49	5.326×10^{-11}	4.961×10^{-21}	8.834×10^{6}	9.177×10^{-5}	1.293×10^{7}	2.336×10^{-4}
50	2.078×10^{-11}	4.623×10^{-21}	9.488×10^{6}	2.186×10^{-8}	1.638×10^{7}	6.130×10^{-4}
51	2.362×10^{-11}	2.889×10^{-21}	9.691×10^{6}	5.628×10^{-6}	1.165×10^{7}	8.569×10^{-4}
52	1.136×10^{-11}	4.910×10^{-21}	1.102×10^{7}	1.517×10^{-7}	1.437×10^{7}	3.354×10^{-4}
53	5.002×10^{-11}	4.276×10^{-22}	1.312×10^{7}	2.369×10^{-6}	1.127×10^{7}	2.562×10^{-4}
54	5.765×10^{-11}	3.896×10^{-21}	1.194×10^{7}	2.295×10^{-8}	1.552×10^{7}	7.453×10^{-5}
55	5.177×10^{-11}	3.667×10^{-21}	1.224×10^{7}	1.229×10^{-8}	1.447×10^{7}	2.068×10^{-4}
56	6.558×10^{-11}	3.321×10^{-21}	1.247×10^{7}	1.236×10^{-9}	1.206×10^{7}	4.113×10^{-4}
57	2.933×10^{-11}	6.782×10^{-21}	8.075×10^{6}	9.440×10^{-10}	1.458×10^{7}	2.284×10^{-4}
58	6.211×10^{-11}	9.229×10^{-21}	7.739×10^{6}	2.154×10^{-4}	1.516×10^{7}	3.174×10^{-5}
59	3.803×10^{-11}	1.962×10^{-20}	1.181×10^{7}	2.671×10^{-5}	1.257×10^{7}	6.774×10^{-4}
60	2.224×10^{-11}	2.635×10^{-20}	1.027×10^{7}	1.188×10^{-4}	1.142×10^{7}	7.905×10^{-4}
61	2.087×10^{-11}	4.830×10^{-21}	7.043×10^{6}	1.144×10^{-5}	1.325×10^{7}	6.264×10^{-5}
62	6.323×10^{-11}	2.800×10^{-21}	1.[illegible]06 × 10^{7}	5.146×10^{-5}	1.497×10^{7}	1.049×10^{-3}
63	3.204×10^{-11}	2.103×10^{-21}	1.052×10^{7}	1.154×10^{-9}	1.128×10^{7}	4.938×10^{-5}
64	2.678×10^{-11}	4.294×10^{-21}	9.622×10^{6}	4.373×10^{-5}	1.349×10^{7}	5.581×10^{-4}
65	4.437×10^{-11}	9.917×10^{-22}	7.166×10^{6}	2.423×10^{-7}	1.587×10^{7}	3.756×10^{-3}
66	3.548×10^{-11}	4.531×10^{-21}	7.395×10^{6}	2.928×10^{-6}	1.691×10^{7}	1.262×10^{-3}
67	1.834×10^{-11}	2.278×10^{-20}	1.097×10^{7}	2.527×10^{-10}	1.667×10^{7}	1.642×10^{-4}
68	3.232×10^{-11}	3.360×10^{-21}	1.420×10^{7}	1.858×10^{-6}	1.422×10^{7}	1.771×10^{-4}
69	4.087×10^{-11}	2.883×10^{-20}	8.414×10^{6}	7.069×10^{-6}	1.190×10^{7}	4.198×10^{-3}
70	3.686×10^{-11}	8.129×10^{-22}	9.019×10^{6}	6.779×10^{-10}	1.158×10^{7}	7.772×10^{-4}

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(7)	X(8)	X(9)	X(10)	X(11)	X(12)
1	0.315	3.671×10^{6}	3.113×10^{-2}	3.108×10^{-10}	1.99	1.47
2	0.493	2.868×10^{6}	9.289×10^{-2}	2.532×10^{-10}	6.79	1.71
3	0.368	1.223×10^{7}	0.114	3.993×10^{-10}	0.605	0.98
4	0.431	2.364×10^{6}	9.542×10^{-2}	2.681×10^{-10}	1.33	5.546×10^{-2}
5	0.486	1.850×10^{6}	8.348×10^{-2}	1.240×10^{-10}	2.44	7.282×10^{-2}
6	0.344	1.258×10^{7}	5.631×10^{-2}	3.196×10^{-10}	6.87	1.57
7	0.34	9.640×10^{6}	9.886×10^{-2}	7.647×10^{-11}	1.58	1.31
8	0.391	5.251×10^{6}	5.421×10^{-2}	1.851×10^{-10}	3.88	1.99
9	0.468	2.418×10^{6}	0.14	1.423×10^{-10}	5.1	0.602
10	0.393	7.557×10^{6}	0.164	1.189×10^{-10}	1.38	0.51
11	0.319	4.246×10^{5}	9.579×10^{-2}	3.270×10^{-10}	1.62	0.236
12	0.384	7.757×10^{6}	0.133	3.634×10^{-10}	0.763	1.52
13	0.374	8.919×10^{6}	9.286×10^{-2}	6.153×10^{-11}	0.459	1.8
14	0.443	1.355×10^{7}	0.219	3.480×10^{-10}	1.51	0.801
15	0.389	4.724×10^{6}	0.23	2.865×10^{-10}	1.76	0.734
16	0.347	1.133×10^{7}	0.31	1.670×10^{-10}	1.03	1.25
17	0.418	3.921×10^{6}	9.759×10^{-2}	9.726×10^{-11}	1.67	1.21
18	0.439	8.317×10^{4}	0.138	1.228×10^{-10}	4.0	0.589
19	0.382	9.835×10^{6}	0.147	3.318×10^{-10}	1.82	1.13
20	0.433	1.208×10^{7}	9.109×10^{-2}	3.680×10^{-10}	4.9	1.2
21	0.406	9.394×10^{6}	0.285	1.763×10^{-10}	4.58	0.694
22	0.371	7.112×10^{6}	9.021×10^{-2}	2.206×10^{-10}	2.22	0.275
23	0.258	1.163×10^{7}	5.061×10^{-2}	2.499×10^{-10}	1.92	0.195
24	0.424	9.000×10^{5}	0.12	1.733×10^{-10}	0.288	1.9
25	0.376	1.292×10^{7}	8.482×10^{-2}	2.988×10^{-10}	0.654	0.225
26	0.37	1.027×10^{7}	3.934×10^{-2}	1.322×10^{-10}	1.41	1.27
27	0.337	4.892×10^{6}	0.266	1.815×10^{-10}	5.2	0.403
28	0.338	3.273×10^{6}	9.445×10^{-2}	2.023×10^{-10}	5.82	0.122
29	0.445	8.226×10^{6}	0.309	2.786×10^{-10}	0.972	1.03
30	0.352	1.070×10^{6}	0.183	1.915×10^{-10}	0.895	1.72
31	0.455	1.378×10^{7}	0.124	7.474×10^{-11}	0.524	0.35
32	0.325	1.602×10^{6}	7.468×10^{-2}	2.732×10^{-10}	0.44	1.51
33	0.287	5.828×10^{6}	0.211	1.032×10^{-10}	1.47	0.101
34	0.385	4.581×10^{6}	9.679×10^{-2}	2.907×10^{-10}	3.58	1.55
35	0.291	4.234×10^{6}	9.403×10^{-2}	9.683×10^{-11}	5.57	1.86
36	0.354	1.104×10^{7}	0.154	1.364×10^{-10}	1.09	1.67
37	0.422	1.055×10^{7}	0.322	8.765×10^{-11}	6.45	0.892
38	0.306	5.752×10^{6}	0.234	8.290×10^{-11}	3.0	0.517
39	0.365	1.236×10^{6}	0.269	1.471×10^{-10}	2.58	1.08
40	0.414	8.762×10^{6}	3.573×10^{-2}	4.290×10^{-10}	5.91	0.442
41	0.367	1.195×10^{7}	9.281×10^{-2}	2.103×10^{-10}	5.36	8.034×10^{-3}
42	0.404	6.689×10^{6}	8.631×10^{-2}	5.340×10^{-11}	3.76	1.64
43	0.327	8.590×10^{6}	0.102	3.495×10^{-10}	3.16	0.639
44	0.388	3.393×10^{5}	9.935×10^{-2}	2.393×10^{-10}	6.18	0.936
45	0.363	7.302×10^{6}	3.718×10^{-2}	2.236×10^{-10}	0.841	0.833
46	0.399	9.090×10^{6}	0.293	2.589×10^{-10}	1.88	0.86
47	0.427	2.733×10^{6}	0.122	2.383×10^{-10}	1.71	1.62
48	0.25	1.645×10^{6}	0.202	4.148×10^{-10}	4.33	1.94
49	0.409	6.525×10^{6}	0.283	3.263×10^{-10}	0.321	0.319
50	0.296	6.377×10^{5}	0.134	1.133×10^{-10}	1.16	0.75
51	0.323	1.003×10^{7}	9.847×10^{-2}	5.553×10^{-11}	0.924	0.565
52	0.449	6.024×10^{6}	0.246	3.937×10^{-10}	4.5	1.76
53	0.377	1.065×10^{7}	0.25	4.046×10^{-10}	0.38	0.683
54	0.309	3.113×10^{6}	9.152×10^{-2}	3.763×10^{-10}	1.27	1.32
55	0.401	2.007×10^{6}	0.24	4.239×10^{-10}	2.76	0.968
56	0.36	3.451×10^{6}	0.329	1.571×10^{-10}	5.49	0.302
57	0.415	6.267×10^{6}	0.106	2.300×10^{-10}	1.23	1.94
58	0.46	1.149×10^{7}	8.922×10^{-2}	1.981×10^{-10}	3.5	1.16
59	0.357	5.483×10^{6}	0.109	3.837×10^{-10}	0.587	1.41
60	0.358	1.264×10^{7}	0.158	2.627×10^{-10}	6.12	1.8
61	0.31	1.089×10^{7}	0.153	2.135×10^{-10}	6.69	0.794
62	0.332	8.124×10^{6}	0.136	3.895×10^{-10}	0.716	1.03
63	0.346	9.512×10^{6}	7.462×10^{-2}	3.734×10^{-10}	3.33	0.375
64	0.379	4.103×10^{6}	0.158	4.090×10^{-10}	4.16	1.09
65	0.349	1.325×10^{7}	0.194	6.505×10^{-11}	2.33	1.37
66	0.396	5.097×10^{6}	0.128	3.075×10^{-10}	2.94	0.471
67	0.411	1.389×10^{7}	6.682×10^{-2}	3.557×10^{-10}	4.74	1.44
68	0.273	1.304×10^{7}	0.126	1.592×10^{-10}	6.4	1.84
69	0.333	7.891×10^{6}	0.131	3.421×10^{-10}	2.01	0.151
70	0.399	6.895×10^{6}	8.111×10^{-2}	3.037×10^{-10}	1.14	1.38

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(13)	X(14)	X(15)	X(16)	X(17)	X(18)
1	0.427	1.824×10^{-2}	712.	5.044×10^{3}	1.0	9.11
2	1.06	2.309×10^{-2}	1.56	1.544×10^{3}	20.8	12.4
3	1.17	1.979×10^{-2}	260.	545.	78.	1.0
4	0.289	2.141×10^{-2}	1.313×10^{3}	1.541×10^{3}	126.	14.1
5	1.81	3.879×10^{-2}	1.391×10^{3}	1.561×10^{3}	1.0	14.8
6	1.0	3.449×10^{-2}	1.273×10^{3}	1.599×10^{3}	9.01	1.0
7	9.245×10^{-2}	7.604×10^{-2}	3.080×10^{3}	1.529×10^{3}	113.	1.0
8	6.358×10^{-2}	2.309×10^{-2}	1.350×10^{3}	795.	12.8	15.
9	1.5	4.694×10^{-2}	1.418×10^{4}	1.470×10^{3}	1.73	1.0
10	0.694	1.143×10^{-2}	1.484×10^{3}	1.524×10^{3}	1.0	15.5
11	0.186	9.755×10^{-2}	182.	1.622×10^{3}	1.0	4.46
12	0.25	3.449×10^{-2}	1.533×10^{4}	2.647×10^{3}	5.95	22.3
13	0.378	3.879×10^{-2}	45.7	1.838×10^{3}	1.0	1.59
14	0.126	3.142×10^{-2}	948.	4.652×10^{3}	34.6	12.8
15	1.75	3.142×10^{-2}	798.	3.901×10^{3}	1.0	3.07
16	1.19	3.142×10^{-2}	1.415×10^{3}	34.	1.0	9.9
17	0.766	0.155	1.001×10^{3}	3.168×10^{3}	138.	11.6
18	1.44	2.059×10^{-2}	7.596×10^{3}	340.	1.0	1.0
19	1.8	0.151	512.	1.551×10^{3}	92.7	8.07
20	0.337	3.142×10^{-2}	1.083×10^{4}	1.116×10^{3}	14.3	54.1
21	0.449	2.309×10^{-2}	9.095×10^{3}	2.754×10^{3}	130.	1.1
22	1.05	2.309×10^{-2}	9.786×10^{3}	1.569×10^{3}	143.	15.5
23	1.99	3.769×10^{-2}	92.5	1.586×10^{3}	11.1	77.5
24	1.64	3.142×10^{-2}	346.	1.559×10^{3}	13.8	7.75
25	1.48	3.142×10^{-2}	1.318×10^{4}	1.748×10^{3}	1.0	1.0
26	1.96	3.142×10^{-2}	428.	2.410×10^{3}	15.3	1.0
27	0.46	3.142×10^{-2}	141.	5.305×10^{3}	10.7	79.5
28	0.95	2.309×10^{-2}	364.	3.456×10^{3}	12.2	1.0
29	0.889	3.142×10^{-2}	1.499×10^{3}	5.179×10^{3}	5.87	6.08
30	1.23	7.604×10^{-2}	878.	1.428×10^{3}	69.3	10.6
31	0.164	6.131×10^{-2}	1.357×10^{3}	3.275×10^{3}	1.0	12.7
32	0.731	2.309×10^{-2}	8.424×10^{3}	4.487×10^{3}	82.5	106.
33	0.973	4.573×10^{-2}	1.433×10^{3}	2.802×10^{3}	6.68	29.4
34	1.32	3.142×10^{-2}	1.254×10^{3}	1.580×10^{3}	1.0	98.4
35	0.662	2.309×10^{-2}	1.227×10^{3}	1.507×10^{3}	1.89	8.81
36	1.55	3.142×10^{-2}	1.324×10^{3}	1.289×10^{3}	9.88	12.
37	0.804	7.604×10^{-2}	216.	386.	2.83	3.41
38	1.72	3.142×10^{-2}	472.	1.992×10^{3}	63.9	1.0
39	0.603	3.142×10^{-2}	829.	1.061×10^{3}	8.74	93.4
40	0.225	2.629×10^{-2}	606.	215.	36.3	1.0
41	0.58	3.142×10^{-2}	2.574×10^{3}	4.973×10^{3}	1.0	10.2
42	1.86	7.604×10^{-2}	1.188×10^{4}	4.803×10^{3}	111.	34.2
43	0.874	1.979×10^{-2}	1.068×10^{3}	766.	1.0	13.7
44	1.7	3.142×10^{-2}	1.454×10^{3}	4.344×10^{3}	10.4	11.2
45	1.6	5.720×10^{-2}	4.198×10^{3}	868.	1.0	103.
46	0.27	3.142×10^{-2}	322.	4.087×10^{3}	3.71	17.7
47	2.006×10^{-2}	4.573×10^{-2}	82.2	2.268×10^{3}	2.79	7.06
48	1.11	3.879×10^{-2}	1.287×10^{3}	4.209×10^{3}	15.9	1.0
49	1.41	1.979×10^{-2}	558.	2.175×10^{3}	99.7	1.0
50	4.275×10^{-2}	3.879×10^{-2}	1.242×10^{3}	2.118×10^{3}	3.87	1.0
51	0.777	2.309×10^{-2}	159.	1.515×10^{3}	10.2	71.8
52	1.94	3.142×10^{-2}	766.	1.572×10^{3}	13.7	62.6
53	1.87	3.879×10^{-2}	201.	1.915×10^{3}	15.5	2.19
54	1.24	0.155	1.153×10^{4}	958.	14.8	60.4
55	0.516	3.142×10^{-2}	5.665×10^{3}	1.512×10^{3}	1.0	14.2
56	1.35	2.309×10^{-2}	1.019×10^{3}	457.	11.4	83.3
57	1.38	3.142×10^{-2}	282.	2.980×10^{3}	1.0	1.0
58	1.6	3.142×10^{-2}	250.	2.576×10^{3}	13.4	37.5
59	1.51	1.824×10^{-2}	1.471×10^{4}	2.907×10^{3}	8.33	6.83
60	1.9	3.142×10^{-2}	1.153×10^{3}	2.385×10^{3}	1.0	2.42
61	1.68	2.309×10^{-2}	1.473×10^{3}	1.590×10^{3}	48.2	1.0
62	0.836	3.142×10^{-2}	303.	671.	14.8	1.0
63	1.26	7.604×10^{-2}	24.8	2.506×10^{3}	7.05	42.3
64	1.11	0.114	1.372×10^{3}	5.515×10^{3}	7.67	1.0
65	1.29	3.142×10^{-2}	5.107×10^{3}	3.663×10^{3}	5.71	4.1
66	0.919	3.142×10^{-2}	108.	3.784×10^{3}	11.7	10.7
67	0.653	7.604×10^{-2}	1.144×10^{3}	1.280×10^{3}	4.46	46.6
68	0.501	1.533×10^{-2}	1.201×10^{3}	2.079×10^{3}	12.5	13.2
69	0.351	0.155	6.839×10^{3}	92.1	53.	5.55
70	0.55	7.604×10^{-2}	650.	1.534×10^{3}	1.12	4.99

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(19)	X(20)	X(21)	X(22)	X(23)	X(24)
1	26.6	285.	39.1	1.79	1.921×10^{-4}	1.600×10^{-5}
2	3.954×10^{4}	336.	47.	35.5	4.143×10^{-4}	9.700×10^{-5}
3	173.	102.	24.1	1.4	6.500×10^{-4}	4.350×10^{-5}
4	939.	476.	45.4	52.4	6.500×10^{-4}	3.426×10^{-5}
5	2.200×10^{4}	88.6	1.55	25.2	6.805×10^{-4}	1.600×10^{-5}
6	124.	379.	41.9	2.01	2.117×10^{-4}	1.600×10^{-5}
7	118.	557.	1.41	24.6	1.812×10^{-4}	6.911×10^{-5}
8	1.540×10^{3}	3.956×10^{3}	19.4	55.8	2.800×10^{-4}	7.385×10^{-5}
9	998.	590.	7.05	1.06	1.879×10^{-4}	1.600×10^{-5}
10	3.962×10^{3}	56.5	1.69	27.9	2.288×10^{-4}	1.600×10^{-5}
11	2.343×10^{3}	619.	2.05	1.47	2.552×10^{-4}	4.637×10^{-5}
12	360.	412.	16.7	1.17	2.541×10^{-4}	7.625×10^{-5}
13	1.325×10^{4}	520.	28.4	6.71	6.375×10^{-4}	9.022×10^{-5}
14	94.	135.	1.65	2.04	2.224×10^{-4}	5.876×10^{-5}
15	377.	2.170×10^{3}	1.09	11.6	5.971×10^{-4}	1.056×10^{-4}
16	74.5	274.	11.4	61.2	1.600×10^{-4}	4.890×10^{-5}
17	43.6	298.	53.5	26.5	3.538×10^{-4}	2.320×10^{-5}
18	13.3	526.	22.6	8.69	7.816×10^{-4}	1.019×10^{-4}
19	3.199×10^{4}	350.	9.23	5.53	1.600×10^{-4}	1.093×10^{-4}
20	805.	3.194×10^{3}	1.96	53.7	2.324×10^{-4}	1.600×10^{-5}
21	2.435×10^{4}	487.	20.9	1.3	1.701×10^{-4}	5.654×10^{-5}
22	134.	220.	2.0	49.7	5.452×10^{-4}	3.879×10^{-5}
23	272.	4.143×10^{3}	7.94	21.2	8.190×10^{-4}	1.188×10^{-4}
24	312.	268.	3.26	13.9	4.716×10^{-4}	1.600×10^{-5}
25	1.857×10^{4}	1.188×10^{3}	55.8	44.8	1.600×10^{-4}	3.735×10^{-5}
26	4.862×10^{4}	322.	3.03	1.28	5.067×10^{-4}	1.600×10^{-5}
27	4.204×10^{4}	2.921×10^{3}	25.5	24.	3.091×10^{-4}	1.600×10^{-5}
28	4.3	307.	17.3	19.9	2.466×10^{-4}	2.686×10^{-5}
29	439.	441.	23.2	3.58	7.240×10^{-4}	2.928×10^{-5}
30	2.064×10^{3}	359.	64.	2.12	3.243×10^{-4}	1.600×10^{-5}
31	2.578×10^{3}	2.762×10^{3}	24.4	11.	2.728×10^{-4}	7.973×10^{-5}
32	37.4	1.582×10^{3}	5.54	1.63	2.668×10^{-4}	5.475×10^{-5}
33	2.704×10^{3}	280.	1.28	2.64	1.600×10^{-4}	1.600×10^{-5}
34	3.514×10^{4}	212.	1.83	7.71	1.600×10^{-4}	4.705×10^{-5}
35	1.864×10^{3}	165.	1.21	9.85	1.600×10^{-4}	1.600×10^{-5}
36	138.	82.3	20.	57.6	1.635×10^{-4}	3.367×10^{-5}
37	55.6	576.	9.42	12.8	2.146×10^{-4}	1.600×10^{-5}
38	327.	4.476×10^{3}	4.04	16.5	1.600×10^{-4}	1.600×10^{-5}
39	2.516×10^{3}	5.047×10^{3}	58.5	1.91	2.048×10^{-4}	6.121×10^{-5}
40	6.802×10^{3}	179.	1.41	2.51	1.600×10^{-4}	1.139×10^{-4}
41	1.318×10^{3}	2.365×10^{3}	15.8	39.9	1.600×10^{-4}	2.034×10^{-5}
42	102.	437.	1.79	21.6	1.600×10^{-4}	1.298×10^{-4}
43	62.4	465.	10.8	37.7	5.592×10^{-4}	9.320×10^{-5}
44	338.	4.669×10^{3}	14.9	19.	1.600×10^{-4}	1.600×10^{-5}
45	198.	345.	37.9	20.3	1.600×10^{-4}	1.916×10^{-5}
46	224.	65.3	32.5	6.37	1.989×10^{-4}	1.600×10^{-5}
47	47.1	372.	1.17	15.1	6.500×10^{-4}	1.109×10^{-4}
48	240.	256.	14.3	61.9	1.600×10^{-4}	1.600×10^{-5}
49	9.734×10^{3}	320.	17.7	43.7	1.600×10^{-4}	4.087×10^{-5}
50	4.468×10^{4}	42.9	22.2	17.4	1.600×10^{-4}	8.596×10^{-5}
51	264.	253.	2.2	4.42	3.850×10^{-4}	6.456×10^{-5}
52	1.488×10^{3}	596.	1.49	10.3	2.988×10^{-4}	1.600×10^{-5}
53	22.5	824.	12.2	1.71	1.600×10^{-4}	1.600×10^{-5}
54	631.	198.	7.46	12.	6.576×10^{-4}	1.609×10^{-5}
55	2.212×10^{3}	398.	4.81	30.8	6.500×10^{-4}	9.566×10^{-5}
56	157.	25.2	52.9	1.08	2.408×10^{-4}	1.263×10^{-4}
57	1.804×10^{3}	1.456×10^{3}	42.3	23.2	1.600×10^{-4}	1.234×10^{-4}
58	308.	300.	34.	22.5	3.044×10^{-4}	6.662×10^{-5}
59	7.845×10^{3}	3.785×10^{3}	29.4	4.58	6.500×10^{-4}	1.214×10^{-4}
60	80.2	389.	6.38	8.55	3.202×10^{-4}	6.153×10^{-5}
61	3.831×10^{4}	128.	60.6	14.1	9.596×10^{-4}	3.106×10^{-5}
62	2.773×10^{4}	3.549×10^{3}	1.0	1.61	6.500×10^{-4}	5.289×10^{-5}
63	185.	240.	18.7	40.6	2.888×10^{-4}	1.022×10^{-4}
64	1.650×10^{4}	12.4	20.3	17.3	6.500×10^{-4}	8.348×10^{-5}
65	220.	150.	2.1	33.2	9.847×10^{-4}	1.600×10^{-5}
66	110.	541.	13.3	15.6	1.765×10^{-4}	1.600×10^{-5}
67	82.7	331.	49.4	1.24	1.600×10^{-4}	2.478×10^{-5}
68	2.928×10^{4}	649.	10.1	1.54	6.500×10^{-4}	1.600×10^{-5}
69	289.	1.791×10^{3}	27.1	18.6	8.957×10^{-4}	1.600×10^{-5}
70	1.121×10^{3}	500.	14.	47.7	8.771×10^{-4}	8.006×10^{-5}

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(25)	X(26)	X(27)	X(28)	X(29)	X(30)
1	4.467×10^{-5}	1.300×10^{-6}	4.794×10^{-6}	5.200×10^{-8}	6.421×10^{-7}	8.169×10^{-10}
2	3.300×10^{-5}	2.003×10^{-7}	5.641×10^{-6}	8.200×10^{-8}	7.672×10^{-7}	8.735×10^{-10}
3	4.933×10^{-5}	1.300×10^{-6}	4.327×10^{-6}	7.558×10^{-8}	1.707×10^{-5}	9.965×10^{-10}
4	5.020×10^{-5}	1.300×10^{-6}	3.903×10^{-6}	6.412×10^{-8}	2.678×10^{-5}	6.724×10^{-10}
5	3.300×10^{-5}	1.300×10^{-6}	4.247×10^{-6}	2.376×10^{-8}	8.493×10^{-6}	7.118×10^{-10}
6	3.300×10^{-5}	3.645×10^{-7}	4.492×10^{-6}	3.300×10^{-8}	2.851×10^{-5}	8.614×10^{-10}
7	3.662×10^{-5}	1.036×10^{-6}	3.403×10^{-6}	1.035×10^{-7}	4.600×10^{-7}	6.909×10^{-10}
8	3.300×10^{-5}	2.768×10^{-7}	9.471×10^{-6}	3.300×10^{-8}	6.218×10^{-7}	9.874×10^{-10}
9	3.300×10^{-5}	1.283×10^{-6}	2.900×10^{-6}	9.496×10^{-8}	2.326×10^{-5}	8.069×10^{-10}
10	3.374×10^{-5}	1.903×10^{-7}	3.075×10^{-6}	8.125×10^{-8}	1.826×10^{-5}	6.978×10^{-10}
11	4.002×10^{-5}	5.847×10^{-7}	4.901×10^{-6}	8.200×10^{-8}	1.667×10^{-5}	9.313×10^{-10}
12	3.300×10^{-5}	2.582×10^{-7}	3.629×10^{-6}	5.234×10^{-8}	7.225×10^{-7}	9.723×10^{-10}
13	4.814×10^{-5}	1.300×10^{-6}	3.463×10^{-6}	5.414×10^{-8}	3.913×10^{-6}	6.849×10^{-10}
14	5.108×10^{-5}	2.904×10^{-7}	1.376×10^{-5}	1.300×10^{-7}	2.231×10^{-5}	9.143×10^{-10}
15	3.300×10^{-5}	1.880×10^{-7}	3.167×10^{-6}	8.200×10^{-8}	2.552×10^{-5}	7.568×10^{-10}
16	3.459×10^{-5}	1.300×10^{-6}	6.013×10^{-6}	4.100×10^{-8}	1.068×10^{-5}	9.284×10^{-10}
17	3.300×10^{-5}	4.016×10^{-7}	1.337×10^{-5}	5.246×10^{-8}	3.657×10^{-5}	9.545×10^{-10}
18	4.542×10^{-5}	1.229×10^{-6}	1.507×10^{-5}	4.197×10^{-8}	5.335×10^{-7}	8.900×10^{-10}
19	3.300×10^{-5}	2.343×10^{-7}	9.326×10^{-6}	4.100×10^{-8}	1.212×10^{-5}	9.155×10^{-10}
20	3.300×10^{-5}	1.300×10^{-6}	6.562×10^{-6}	1.572×10^{-7}	4.860×10^{-7}	9.094×10^{-10}
21	3.300×10^{-5}	8.606×10^{-7}	1.150×10^{-5}	5.350×10^{-8}	4.493×10^{-7}	6.541×10^{-10}
22	4.155×10^{-5}	2.155×10^{-7}	2.721×10^{-6}	3.806×10^{-8}	1.358×10^{-5}	9.419×10^{-10}
23	3.300×10^{-5}	1.198×10^{-6}	5.785×10^{-6}	1.489×10^{-7}	7.093×10^{-6}	7.823×10^{-10}
24	3.300×10^{-5}	1.781×10^{-7}	1.583×10^{-5}	1.300×10^{-7}	4.316×10^{-7}	9.007×10^{-10}
25	3.724×10^{-5}	1.770×10^{-7}	8.735×10^{-6}	6.991×10^{-8}	6.078×10^{-7}	9.700×10^{-10}
26	3.686×10^{-5}	1.300×10^{-6}	1.580×10^{-5}	2.979×10^{-8}	3.759×10^{-7}	8.486×10^{-10}
27	4.692×10^{-5}	1.300×10^{-6}	5.260×10^{-6}	8.496×10^{-8}	6.512×10^{-7}	8.919×10^{-10}
28	3.300×10^{-5}	3.303×10^{-7}	5.004×10^{-6}	1.233×10^{-7}	3.442×10^{-7}	8.655×10^{-10}
29	3.300×10^{-5}	5.280×10^{-7}	1.303×10^{-5}	3.300×10^{-8}	5.100×10^{-6}	7.177×10^{-10}
30	3.300×10^{-5}	3.497×10^{-7}	5.933×10^{-6}	8.200×10^{-8}	3.468×10^{-5}	9.830×10^{-10}
31	3.300×10^{-5}	1.300×10^{-6}	1.473×10^{-5}	8.200×10^{-8}	2.417×10^{-5}	8.996×10^{-10}
32	3.300×10^{-5}	1.163×10^{-6}	5.392×10^{-6}	5.830×10^{-8}	5.355×10^{-7}	7.430×10^{-10}
33	3.300×10^{-5}	1.990×10^{-7}	6.170×10^{-6}	1.292×10^{-7}	1.537×10^{-5}	8.533×10^{-10}
34	3.300×10^{-5}	3.384×10^{-7}	1.320×10^{-5}	1.300×10^{-7}	4.194×10^{-7}	9.615×10^{-10}
35	3.300×10^{-5}	1.300×10^{-6}	1.356×10^{-5}	8.200×10^{-8}	5.487×10^{-6}	7.359×10^{-10}
36	4.872×10^{-5}	1.709×10^{-7}	1.091×10^{-5}	6.761×10^{-8}	7.996×10^{-7}	7.043×10^{-10}
37	3.516×10^{-5}	2.487×10^{-7}	3.245×10^{-6}	1.315×10^{-7}	3.231×10^{-5}	7.884×10^{-10}
38	3.300×10^{-5}	1.068×10^{-6}	1.171×10^{-5}	4.638×10^{-8}	6.654×10^{-7}	9.591×10^{-10}
39	4.429×10^{-5}	2.274×10^{-7}	7.223×10^{-6}	5.190×10^{-8}	8.297×10^{-7}	6.666×10^{-10}
40	3.300×10^{-5}	1.115×10^{-6}	1.489×10^{-5}	5.200×10^{-8}	2.742×10^{-5}	8.288×10^{-10}
41	3.544×10^{-5}	3.279×10^{-7}	8.528×10^{-6}	4.296×10^{-8}	7.793×10^{-7}	9.925×10^{-10}
42	3.809×10^{-5}	8.836×10^{-7}	7.252×10^{-6}	1.300×10^{-7}	5.925×10^{-7}	9.357×10^{-10}
43	3.300×10^{-5}	7.019×10^{-7}	1.548×10^{-5}	1.300×10^{-7}	4.012×10^{-5}	7.725×10^{-10}
44	5.148×10^{-5}	2.114×10^{-7}	1.441×10^{-5}	8.770×10^{-8}	3.626×10^{-5}	7.647×10^{-10}
45	3.892×10^{-5}	3.884×10^{-7}	1.387×10^{-5}	1.300×10^{-7}	1.315×10^{-5}	6.554×10^{-10}
46	3.300×10^{-5}	1.079×10^{-6}	2.994×10^{-6}	1.300×10^{-7}	5.620×10^{-7}	8.200×10^{-10}
47	4.127×10^{-5}	2.658×10^{-7}	1.549×10^{-5}	1.300×10^{-7}	8.982×10^{-6}	7.976×10^{-10}
48	3.300×10^{-5}	1.300×10^{-6}	3.347×10^{-6}	4.100×10^{-8}	2.973×10^{-5}	7.276×10^{-10}
49	3.974×10^{-5}	3.756×10^{-7}	4.161×10^{-6}	1.300×10^{-7}	7.375×10^{-7}	6.767×10^{-10}
50	3.300×10^{-5}	1.300×10^{-6}	1.516×10^{-5}	1.131×10^{-7}	3.935×10^{-5}	8.791×10^{-10}
51	3.300×10^{-5}	3.114×10^{-7}	3.561×10^{-6}	2.316×10^{-8}	8.171×10^{-7}	8.566×10^{-10}
52	4.746×10^{-5}	1.300×10^{-6}	3.741×10^{-6}	8.200×10^{-8}	3.095×10^{-5}	9.454×10^{-10}
53	3.300×10^{-5}	1.300×10^{-6}	1.447×10^{-5}	1.300×10^{-7}	8.455×10^{-7}	7.200×10^{-10}
54	4.617×10^{-5}	3.150×10^{-7}	4.663×10^{-6}	3.732×10^{-8}	1.297×10^{-6}	7.940×10^{-10}
55	3.581×10^{-5}	1.300×10^{-6}	1.396×10^{-5}	5.336×10^{-8}	3.862×10^{-7}	8.039×10^{-10}
56	4.325×10^{-5}	3.601×10^{-7}	4.022×10^{-6}	1.300×10^{-7}	4.965×10^{-7}	9.792×10^{-10}
57	3.339×10^{-5}	1.300×10^{-6}	2.620×10^{-6}	1.300×10^{-7}	6.820×10^{-7}	9.211×10^{-10}
58	4.039×10^{-5}	9.535×10^{-7}	6.425×10^{-6}	3.390×10^{-8}	2.113×10^{-5}	7.784×10^{-10}
59	3.300×10^{-5}	4.240×10^{-7}	6.307×10^{-6}	1.300×10^{-7}	3.790×10^{-5}	7.316×10^{-10}
60	3.300×10^{-5}	3.998×10^{-7}	7.946×10^{-6}	3.300×10^{-8}	7.049×10^{-7}	6.861×10^{-10}
61	3.300×10^{-5}	6.383×10^{-7}	1.414×10^{-5}	1.429×10^{-7}	7.406×10^{-7}	7.073×10^{-10}
62	4.250×10^{-5}	2.178×10^{-7}	3.863×10^{-6}	5.022×10^{-8}	2.357×10^{-6}	8.301×10^{-10}
63	4.273×10^{-5}	1.300×10^{-6}	1.122×10^{-5}	1.605×10^{-8}	5.167×10^{-7}	7.532×10^{-10}
64	3.913×10^{-5}	2.875×10^{-7}	8.099×10^{-6}	1.300×10^{-7}	5.730×10^{-7}	7.673×10^{-10}
65	3.413×10^{-5}	7.726×10^{-7}	1.029×10^{-5}	9.808×10^{-8}	3.393×10^{-5}	8.805×10^{-10}
66	3.300×10^{-5}	1.611×10^{-7}	1.270×10^{-5}	4.100×10^{-8}	1.994×10^{-5}	8.442×10^{-10}
67	3.300×10^{-5}	2.406×10^{-7}	5.535×10^{-6}	5.200×10^{-8}	8.738×10^{-7}	6.613×10^{-10}
68	5.011×10^{-5}	2.974×10^{-7}	1.234×10^{-5}	8.200×10^{-8}	8.544×10^{-7}	8.141×10^{-10}
69	3.300×10^{-5}	2.353×10^{-7}	9.993×10^{-6}	6.138×10^{-8}	3.480×10^{-7}	8.398×10^{-10}
70	3.770×10^{-5}	2.570×10^{-7}	2.816×10^{-6}	1.300×10^{-7}	4.008×10^{-7}	7.464×10^{-10}

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(31)	X(32)	X(33)	X(34)	X(35)	X(36)
1	5.218×10^{-5}	3.300×10^{-8}	7.0	1.650×10^{11}	8.892×10^{10}	7.966×10^{10}
2	6.289×10^{-5}	3.300×10^{-8}	3.0	1.410×10^{11}	1.830×10^{11}	1.643×10^{11}
3	4.100×10^{-5}	3.094×10^{-8}	2.0	8.374×10^{10}	2.689×10^{11}	1.757×10^{10}
4	3.365×10^{-5}	3.300×10^{-8}	1.0	2.396×10^{11}	5.564×10^{10}	2.114×10^{11}
5	1.698×10^{-5}	1.615×10^{-8}	5.0	9.230×10^{10}	2.297×10^{11}	3.123×10^{11}
6	5.833×10^{-6}	2.798×10^{-8}	1.0	1.059×10^{11}	3.424×10^{10}	1.193×10^{11}
7	4.553×10^{-5}	2.072×10^{-8}	3.0	7.231×10^{10}	3.772×10^{10}	1.113×10^{11}
8	6.316×10^{-6}	2.735×10^{-8}	4.0	3.015×10^{11}	6.328×10^{10}	1.363×10^{11}
9	7.207×10^{-5}	1.300×10^{-8}	3.0	1.013×10^{11}	1.128×10^{11}	2.797×10^{10}
10	3.539×10^{-5}	5.294×10^{-9}	5.0	1.628×10^{11}	2.100×10^{11}	1.923×10^{11}
11	3.066×10^{-5}	1.278×10^{-8}	4.0	2.948×10^{11}	2.570×10^{11}	3.630×10^{10}
12	5.379×10^{-6}	3.300×10^{-8}	2.0	6.269×10^{10}	1.927×10^{11}	3.004×10^{11}
13	5.738×10^{-6}	1.058×10^{-8}	2.0	7.528×10^{10}	1.953×10^{11}	1.709×10^{11}
14	6.284×10^{-6}	1.091×10^{-8}	3.0	1.999×10^{11}	1.393×10^{11}	2.913×10^{11}
15	1.836×10^{-5}	3.300×10^{-8}	1.0	2.555×10^{11}	8.750×10^{10}	1.418×10^{10}
16	4.100×10^{-5}	1.300×10^{-8}	2.0	3.100×10^{11}	2.902×10^{11}	1.266×10^{11}
17	4.100×10^{-5}	2.866×10^{-8}	8.0	1.568×10^{11}	2.070×10^{11}	1.770×10^{11}
18	2.380×10^{-5}	3.180×10^{-8}	5.0	1.506×10^{11}	2.815×10^{11}	2.600×10^{11}
19	4.974×10^{-5}	3.300×10^{-8}	6.0	2.978×10^{10}	6.794×10^{10}	1.408×10^{11}
20	9.366×10^{-6}	2.650×10^{-8}	2.0	2.724×10^{11}	2.779×10^{11}	1.571×10^{11}
21	1.111×10^{-5}	3.125×10^{-8}	3.0	2.809×10^{11}	2.483×10^{11}	2.482×10^{11}
22	5.335×10^{-6}	2.310×10^{-8}	6.0	2.516×10^{11}	1.051×10^{11}	4.385×10^{10}
23	6.051×10^{-6}	1.300×10^{-8}	4.0	3.057×10^{11}	1.472×10^{11}	5.196×10^{10}
24	6.171×10^{-6}	9.947×10^{-9}	2.0	2.136×10^{11}	3.930×10^{10}	1.307×10^{11}
25	4.100×10^{-5}	1.030×10^{-8}	5.0	3.136×10^{11}	1.652×10^{10}	2.532×10^{11}
26	5.706×10^{-6}	1.456×10^{-8}	2.0	1.783×10^{11}	2.648×10^{11}	6.528×10^{9}
27	4.136×10^{-5}	1.300×10^{-8}	6.0	1.117×10^{11}	1.256×10^{11}	2.707×10^{11}
28	2.836×10^{-5}	6.739×10^{-9}	1.0	1.988×10^{11}	1.010×10^{11}	2.821×10^{11}
29	2.129×10^{-5}	8.023×10^{-9}	3.0	1.224×10^{11}	2.488×10^{11}	2.429×10^{10}
30	4.100×10^{-5}	3.175×10^{-9}	4.0	2.402×10^{11}	2.172×10^{11}	2.280×10^{11}
31	2.015×10^{-5}	3.300×10^{-8}	2.0	4.895×10^{10}	2.243×10^{11}	6.187×10^{10}
32	4.100×10^{-5}	1.337×10^{-8}	4.0	1.941×10^{11}	2.953×10^{10}	5.813×10^{10}
33	4.807×10^{-5}	2.511×10^{-8}	3.0	9.556×10^{10}	3.008×10^{11}	2.083×10^{11}
34	4.100×10^{-5}	3.300×10^{-8}	2.0	7.915×10^{10}	1.724×10^{11}	2.654×10^{11}
35	5.623×10^{-6}	3.031×10^{-8}	9.0	2.657×10^{11}	2.206×10^{11}	7.636×10^{10}
36	6.705×10^{-5}	3.300×10^{-8}	5.0	5.982×10^{10}	1.614×10^{11}	8.829×10^{10}
37	5.540×10^{-6}	3.300×10^{-8}	4.0	1.885×10^{11}	2.355×10^{11}	1.453×10^{11}
38	4.100×10^{-5}	2.557×10^{-8}	3.0	8.225×10^{9}	1.206×10^{11}	2.795×10^{11}
39	6.497×10^{-6}	5.855×10^{-9}	2.0	2.105×10^{11}	1.165×10^{11}	5.588×10^{10}
40	5.853×10^{-5}	4.094×10^{-9}	3.0	1.688×10^{11}	1.807×10^{11}	2.253×10^{11}
41	4.100×10^{-5}	5.028×10^{-9}	3.0	3.893×10^{10}	2.584×10^{11}	4.162×10^{10}
42	6.198×10^{-5}	3.784×10^{-9}	3.0	2.279×10^{11}	1.331×10^{11}	7.277×10^{10}
43	6.134×10^{-6}	8.631×10^{-9}	3.0	5.687×10^{9}	5.160×10^{9}	9.521×10^{10}
44	3.825×10^{-5}	3.242×10^{-8}	1.0	2.081×10^{11}	7.070×10^{10}	2.404×10^{11}
45	1.167×10^{-5}	1.300×10^{-8}	3.0	3.161×10^{10}	1.754×10^{11}	1.160×10^{11}
46	7.058×10^{-5}	1.800×10^{-8}	2.0	1.363×10^{11}	1.168×10^{10}	8.589×10^{10}
47	4.100×10^{-5}	1.242×10^{-8}	4.0	1.259×10^{11}	2.745×10^{11}	2.201×10^{11}
48	6.447×10^{-6}	1.300×10^{-8}	2.0	6.732×10^{10}	3.131×10^{11}	1.005×10^{11}
49	1.461×10^{-5}	9.475×10^{-9}	4.0	1.830×10^{10}	2.034×10^{11}	1.042×10^{11}
50	4.100×10^{-5}	2.810×10^{-8}	2.0	2.895×10^{11}	1.788×10^{10}	1.838×10^{11}
51	4.100×10^{-5}	1.300×10^{-8}	1.0	1.743×10^{11}	6.071×10^{10}	2.937×10^{11}
52	3.161×10^{-5}	1.230×10^{-8}	3.0	1.452×10^{11}	2.342×10^{10}	1.537×10^{11}
53	4.100×10^{-5}	2.933×10^{-8}	4.0	2.454×10^{11}	2.428×10^{11}	3.080×10^{11}
54	4.670×10^{-5}	1.676×10^{-8}	1.0	5.588×10^{10}	1.422×10^{11}	3.054×10^{11}
55	6.503×10^{-5}	1.170×10^{-8}	4.0	4.599×10^{10}	4.607×10^{10}	7.848×10^{9}
56	5.889×10^{-6}	1.300×10^{-8}	2.0	1.286×10^{11}	2.336×10^{11}	6.670×10^{10}
57	5.489×10^{-6}	1.300×10^{-8}	6.0	1.562×10^{10}	1.301×10^{11}	2.852×10^{11}
58	2.676×10^{-5}	1.067×10^{-8}	3.0	2.877×10^{11}	1.575×10^{11}	2.361×10^{11}
59	5.516×10^{-5}	2.249×10^{-8}	5.0	2.688×10^{11}	3.061×10^{11}	2.327×10^{11}
60	4.100×10^{-5}	7.287×10^{-9}	1.0	2.231×10^{11}	9.484×10^{10}	1.977×10^{11}
61	5.444×10^{-5}	3.300×10^{-8}	3.0	2.333×10^{11}	1.081×10^{11}	1.495×10^{11}
62	4.023×10^{-5}	1.300×10^{-8}	7.0	2.579×10^{11}	5.148×10^{10}	2.507×10^{11}
63	4.100×10^{-5}	3.300×10^{-8}	5.0	2.785×10^{11}	8.273×10^{10}	1.779×10^{11}
64	5.211×10^{-6}	1.300×10^{-8}	4.0	1.834×10^{11}	1.645×10^{11}	1.894×10^{11}
65	4.100×10^{-5}	1.300×10^{-8}	4.0	1.039×10^{11}	7.488×10^{10}	2.132×10^{11}
66	4.374×10^{-5}	2.184×10^{-8}	2.0	1.500×10^{11}	3.108×10^{11}	3.307×10^{10}
67	4.100×10^{-5}	1.133×10^{-8}	6.0	2.204×10^{11}	1.521×10^{11}	1.626×10^{11}
68	5.756×10^{-5}	1.155×10^{-8}	4.0	3.714×10^{10}	2.950×10^{11}	2.728×10^{11}
69	5.953×10^{-6}	1.868×10^{-8}	5.0	2.222×10^{10}	1.876×10^{11}	1.069×10^{11}
70	6.880×10^{-5}	1.206×10^{-8}	1.0	1.181×10^{11}	2.860×10^{11}	2.018×10^{11}

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(37)	X(38)	X(39)	X(40)	X(41)	X(42)
1	1.305×10^{11}	1.098×10^{11}	2.842×10^{11}	1.399×10^{11}	4.784×10^{10}	2.542×10^{11}
2	1.261×10^{11}	2.332×10^{10}	1.395×10^{11}	2.406×10^{11}	6.075×10^{9}	1.408×10^{11}
3	2.453×10^{11}	6.757×10^{10}	4.166×10^{10}	1.666×10^{11}	1.111×10^{11}	4.005×10^{10}
4	1.258×10^{10}	1.045×10^{11}	1.352×10^{11}	2.957×10^{11}	2.639×10^{11}	1.943×10^{11}
5	9.012×10^{10}	2.354×10^{11}	1.487×10^{11}	2.268×10^{11}	1.920×10^{11}	2.807×10^{11}
6	2.123×10^{11}	2.596×10^{11}	2.924×10^{11}	6.659×10^{10}	1.961×10^{11}	2.619×10^{11}
7	2.831×10^{11}	1.307×10^{11}	1.214×10^{11}	2.678×10^{11}	2.368×10^{11}	2.443×10^{10}
8	2.070×10^{11}	1.747×10^{11}	3.427×10^{10}	3.078×10^{11}	2.540×10^{11}	2.039×10^{11}
9	2.280×10^{11}	2.613×10^{10}	6.069×10^{10}	2.637×10^{11}	1.554×10^{11}	2.880×10^{11}
10	2.366×10^{11}	2.510×10^{11}	1.755×10^{11}	2.315×10^{11}	7.830×10^{10}	1.309×10^{11}
11	1.757×10^{11}	4.496×10^{10}	2.553×10^{11}	2.111×10^{11}	2.335×10^{10}	1.427×10^{11}
12	1.854×10^{11}	2.273×10^{11}	1.165×10^{11}	1.253×10^{11}	6.152×10^{10}	1.979×10^{11}
13	3.131×10^{11}	3.098×10^{11}	6.994×10^{10}	2.532×10^{11}	1.848×10^{11}	2.414×10^{11}
14	2.144×10^{11}	8.195×10^{10}	2.428×10^{11}	1.189×10^{11}	9.868×10^{10}	2.086×10^{11}
15	2.408×10^{11}	1.227×10^{11}	3.062×10^{11}	1.804×10^{11}	2.454×10^{11}	7.839×10^{10}
16	6.769×10^{10}	1.220×10^{10}	3.098×10^{11}	2.261×10^{11}	9.420×10^{10}	1.342×10^{11}
17	1.017×10^{11}	2.177×10^{11}	2.361×10^{11}	1.550×10^{10}	9.233×10^{10}	2.974×10^{11}
18	2.351×10^{11}	2.658×10^{11}	1.924×10^{11}	5.902×10^{10}	3.091×10^{11}	5.379×10^{10}
19	1.531×10^{11}	1.252×10^{11}	3.124×10^{11}	2.861×10^{11}	2.873×10^{11}	2.797×10^{11}
20	1.774×10^{11}	1.809×10^{11}	1.530×10^{11}	1.741×10^{11}	1.281×10^{11}	2.502×10^{11}
21	2.727×10^{11}	3.962×10^{10}	2.772×10^{11}	1.803×10^{10}	1.090×10^{11}	5.916×10^{10}
22	1.926×10^{11}	1.526×10^{11}	4.812×10^{10}	2.439×10^{10}	4.481×10^{10}	3.081×10^{11}
23	1.389×10^{11}	2.571×10^{11}	7.140×10^{10}	1.231×10^{11}	2.416×10^{11}	2.727×10^{11}
24	1.887×10^{10}	5.135×10^{10}	2.717×10^{11}	2.486×10^{11}	6.757×10^{10}	2.176×10^{11}
25	2.688×10^{11}	2.669×10^{11}	2.063×10^{11}	1.551×10^{11}	1.752×10^{11}	1.246×10^{11}
26	2.650×10^{11}	2.311×10^{11}	9.917×10^{10}	1.310×10^{11}	2.277×10^{11}	2.156×10^{11}
27	1.868×10^{11}	2.781×10^{11}	2.604×10^{11}	1.096×10^{11}	1.873×10^{11}	8.268×10^{9}
28	6.198×10^{10}	7.678×10^{10}	1.698×10^{11}	1.953×10^{11}	2.511×10^{11}	2.904×10^{11}
29	1.114×10^{11}	1.172×10^{11}	1.103×10^{11}	1.134×10^{11}	2.025×10^{10}	5.220×10^{10}
30	1.703×10^{11}	1.607×10^{11}	2.154×10^{11}	7.931×10^{10}	3.015×10^{11}	8.898×10^{10}
31	1.014×10^{10}	2.034×10^{11}	2.325×10^{11}	1.365×10^{11}	2.602×10^{11}	1.635×10^{11}
32	1.442×10^{11}	3.026×10^{11}	2.850×10^{11}	1.996×10^{11}	2.148×10^{11}	8.791×10^{10}
33	1.501×10^{11}	2.160×10^{11}	2.287×10^{11}	7.494×10^{10}	1.041×10^{11}	1.748×10^{11}
34	3.015×10^{11}	1.567×10^{11}	1.284×10^{11}	1.539×10^{11}	2.092×10^{11}	2.077×10^{11}
35	1.159×10^{11}	7.286×10^{10}	4.369×10^{10}	1.833×10^{11}	2.720×10^{11}	7.948×10^{10}
36	2.036×10^{11}	3.017×10^{11}	1.089×10^{11}	9.714×10^{10}	1.178×10^{11}	1.134×10^{11}
37	7.747×10^{10}	2.425×10^{11}	7.887×10^{10}	4.812×10^{10}	7.135×10^{10}	1.646×10^{11}
38	5.228×10^{10}	2.727×10^{11}	1.047×10^{11}	2.767×10^{11}	1.613×10^{10}	2.378×10^{11}
39	3.051×10^{11}	9.451×10^{10}	2.448×10^{11}	1.484×10^{11}	1.513×10^{11}	3.063×10^{11}
40	1.644×10^{11}	3.127×10^{11}	2.667×10^{11}	6.493×10^{10}	1.773×10^{11}	7.278×10^{10}
41	1.631×10^{11}	9.977×10^{10}	2.903×10^{10}	2.910×10^{11}	1.292×10^{11}	4.382×10^{10}
42	8.675×10^{10}	8.627×10^{10}	6.522×10^{10}	7.446×10^{10}	1.437×10^{11}	1.207×10^{11}
43	3.082×10^{11}	5.353×10^{10}	1.881×10^{11}	1.867×10^{11}	2.047×10^{11}	1.772×10^{11}
44	1.352×10^{11}	1.904×10^{11}	1.623×10^{11}	2.376×10^{11}	1.663×10^{11}	3.539×10^{10}
45	4.137×10^{10}	5.496×10^{9}	1.809×10^{11}	1.020×10^{11}	5.254×10^{10}	2.075×10^{10}
46	2.222×10^{11}	2.094×10^{11}	9.411×10^{10}	1.929×10^{11}	2.234×10^{11}	2.352×10^{11}
47	2.916×10^{11}	1.834×10^{11}	1.668×10^{11}	2.614×10^{11}	3.821×10^{10}	1.070×10^{11}
48	5.947×10^{10}	2.844×10^{11}	2.494×10^{11}	2.840×10^{11}	8.692×10^{10}	6.399×10^{10}
49	2.534×10^{11}	1.349×10^{11}	1.560×10^{11}	9.074×10^{10}	2.329×10^{11}	2.686×10^{11}
50	1.009×10^{11}	1.444×10^{11}	1.596×10^{10}	2.973×10^{10}	1.466×10^{11}	2.447×10^{11}
51	1.064×10^{11}	3.155×10^{10}	2.104×10^{11}	5.512×10^{10}	2.688×10^{11}	4.524×10^{9}
52	1.585×10^{11}	1.396×10^{11}	1.271×10^{11}	3.504×10^{10}	2.962×10^{11}	1.453×10^{10}
53	2.762×10^{11}	1.916×10^{11}	5.379×10^{10}	2.469×10^{11}	1.405×10^{11}	2.626×10^{11}
54	2.180×10^{11}	1.498×10^{11}	1.052×10^{10}	2.042×10^{11}	1.334×10^{11}	2.293×10^{11}
55	2.912×10^{10}	2.915×10^{11}	1.968×10^{11}	3.954×10^{10}	1.636×10^{11}	3.017×10^{11}
56	3.721×10^{10}	2.939×10^{11}	2.234×10^{11}	3.028×10^{11}	1.206×10^{11}	9.389×10^{10}
57	4.448×10^{10}	5.694×10^{10}	9.081×10^{10}	3.270×10^{9}	8.198×10^{10}	1.032×10^{11}
58	2.949×10^{11}	2.461×10^{11}	2.996×10^{11}	2.181×10^{11}	2.918×10^{10}	1.591×10^{11}
59	2.523×10^{11}	9.054×10^{10}	3.855×10^{10}	2.170×10^{11}	1.716×10^{11}	1.534×10^{11}
60	3.040×10^{10}	1.649×10^{11}	8.087×10^{10}	3.329×10^{10}	1.179×10^{10}	1.687×10^{11}
61	1.216×10^{11}	2.801×10^{11}	1.441×10^{11}	1.452×10^{11}	3.198×10^{10}	2.948×10^{10}
62	4.906×10^{9}	2.249×10^{11}	8.768×10^{10}	1.707×10^{11}	4.149×10^{10}	9.740×10^{10}
63	2.863×10^{11}	9.598×10^{9}	1.807×10^{10}	1.611×10^{11}	2.207×10^{11}	2.240×10^{11}
64	7.210×10^{10}	6.356×10^{10}	1.841×10^{11}	2.729×10^{11}	3.063×10^{11}	1.462×10^{11}
65	1.952×10^{11}	1.144×10^{11}	2.178×10^{11}	2.977×10^{11}	2.000×10^{11}	1.819×10^{11}
66	8.270×10^{10}	1.982×10^{11}	3.486×10^{9}	4.530×10^{10}	3.155×10^{11}	1.872×10^{11}
67	2.378×10^{10}	2.052×10^{11}	2.190×10^{10}	3.155×10^{11}	2.757×10^{11}	6.622×10^{10}
68	4.993×10^{10}	1.813×10^{10}	2.624×10^{11}	9.565×10^{10}	2.924×10^{11}	3.134×10^{11}
69	2.604×10^{11}	3.782×10^{10}	2.008×10^{11}	8.594×10^{10}	5.686×10^{10}	3.013×10^{10}
70	9.592×10^{10}	1.716×10^{11}	2.950×10^{11}	1.177×10^{10}	2.799×10^{11}	1.165×10^{11}

TABLE C-3a. LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO (concluded)

RUN NO.	X(43)	X(44)	X(45)	X(46)	X(47)	X(48)	X(49)	X(50)	X(51)
1	143.	87.8	43.3	86.	69.6	66.6	29.6	68.9	130.
2	45.8	53.7	31.5	27.9	44.3	30.4	82.8	112.	61.3
3	59.6	36.4	17.7	18.3	7.29	89.	120.	131.	123.
4	94.7	31.6	124.	131.	23.5	43.5	12.7	23.4	113.
5	91.8	22.8	2.25	34.8	112.	22.5	115.	90.8	115.
6	9.73	70.	44.5	144.	129.	24.7	138.	79.3	55.9
7	134.	76.4	3.34	75.1	107.	32.8	4.21	35.6	43.1
8	88.7	27.6	114.	59.7	104.	49.	124.	135.	89.
9	25.	137.	138.	115.	74.9	26.2	35.8	56.3	49.2
10	54.8	83.2	126.	118.	31.2	106.	46.9	47.1	136.
11	6.39	98.1	107.	25.4	126.	123.	127.	11.2	128.
12	116.	108.	76.	80.5	1.13	12.1	106.	1.12	18.2
13	37.6	136.	23.7	70.5	101.	56.9	87.6	92.9	126.
14	120.	9.21	72.1	38.1	140.	64.	19.3	39.3	105.
15	106.	50.8	109.	31.8	14.7	138.	38.8	117.	75.2
16	35.2	97.5	27.9	139.	88.3	79.4	125.	115.	45.1
17	129.	119.	89.9	41.2	119.	131.	91.3	32.7	19.6
18	40.	50.3	120.	50.5	94.8	121.	20.1	71.4	57.1
19	79.2	84.3	63.5	65.	112.	112.	16.	103.	116.
20	62.5	57.1	35.8	104.	55.	91.1	27.3	61.8	90.4
21	70.5	144.	67.5	46.4	96.7	83.7	144.	44.4	145.
22	47.7	113.	85.3	4.76	135.	45.1	23.	125.	23.6
23	42.6	140.	140.	100.	75.9	13.8	63.	11.4	98.6
24	82.1	101.	70.1	121.	116.	140.	76.5	15.9	81.9
25	98.4	93.	22.	23.4	3.08	100.	41.9	53.2	72.6
26	123.	1.58	95.7	63.7	59.2	85.9	52.	50.2	3.65
27	53.1	91.3	55.8	74.1	67.5	137.	25.6	133.	79.7
28	31.4	35.6	102.	13.4	29.4	40.4	98.6	144.	38.6
29	32.9	111.	105.	134.	63.4	103.	6.58	119.	1.25
30	14.6	42.9	37.1	17.	13.3	6.23	9.13	19.9	121.
31	16.5	103.	98.7	6.25	39.	72.8	48.5	130.	133.
32	2.9	46.8	14.8	95.9	85.8	114.	113.	108.	37.4
33	116.	6.52	26.9	124.	40.6	5.05	74.3	141.	9.91
34	19.	117.	131.	103.	134.	59.4	1.43	64.7	108.
35	139.	127.	93.	11.1	19.7	129.	117.	77.8	67.4
36	3.62	18.5	115.	87.5	132.	1.75	109.	76.2	119.
37	13.3	20.2	5.61	108.	51.7	142.	44.	18.4	17.2
38	90.6	94.1	32.2	21.2	25.7	117.	130.	8.58	50.4
39	135.	11.1	74.1	62.6	90.4	55.2	46.1	123.	95.2
40	40.2	16.	127.	53.	60.9	119.	87.4	31.8	69.1
41	56.7	124.	79.4	92.	144.	95.2	94.8	52.	63.9
42	107.	24.9	38.6	138.	6.88	108.	96.3	86.8	141.
43	127.	73.2	12.1	98.	57.5	126.	37.2	105.	110.
44	76.8	40.5	88.3	44.9	82.7	19.2	133.	43.4	84.4
45	72.8	64.	51.6	7.66	72.5	15.4	77.3	81.4	14.5
46	109.	13.	130.	12.1	99.4	95.8	120.	28.8	52.5
47	26.8	121.	53.3	48.6	9.93	7.4	68.9	88.7	33.8
48	111.	62.	135.	33.4	43.5	38.2	14.8	40.5	103.
49	23.4	125.	83.2	43.9	34.2	109.	132.	36.6	7.12
50	86.2	106.	85.4	118.	110.	47.7	55.9	127.	41.5
51	68.7	59.2	100.	111.	122.	70.6	31.9	6.05	34.1
52	96.7	131.	57.1	37.8	102.	10.4	136.	114.	31.6
53	132.	71.8	121.	109.	123.	35.8	62.3	140.	93.4
54	51.9	107.	117.	72.1	32.6	145.	110.	139.	102.
55	102.	67.	48.5	91.1	48.4	37.6	101.	25.9	86.7
56	138.	114.	40.4	82.3	116.	67.5	71.1	60.2	65.3
57	75.	3.35	142.	135.	78.1	98.5	68.7	98.5	108.
58	125.	143.	111.	124.	15.7	78.3	59.3	108.	24.9
59	99.9	13.5	11.	57.9	141.	135.	93.3	14.	47.6
60	49.4	99.	47.2	1.09	126.	73.6	10.5	56.6	142.
61	62.9	77.3	59.7	114.	66.	115.	53.3	97.2	60.4
62	113.	86.4	64.9	129.	84.7	20.6	66.3	121.	78.4
63	28.8	56.2	15.5	85.2	19.1	50.9	57.2	3.38	27.8
64	20.9	66.	8.13	95.3	93.3	54.4	104.	94.7	97.4
65	84.2	33.3	144.	67.5	48.	60.7	143.	23.8	73.6
66	122.	134.	20.4	142.	36.	91.8	79.6	69.2	137.
67	65.5	38.8	94.3	55.6	80.4	127.	84.	101.	27.2
68	9.2	79.7	62.2	77.6	24.3	75.3	31.9	74.4	12.6
69	78.8	44.3	134.	128.	53.9	28.2	102.	84.1	132.
70	144.	129.	78.1	27.7	138.	82.4	140.	66.1	8.56

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS FOR MULTIPLE INTRUSION SCENARIO

RUN NO.	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)
1	32.	35.	6.	41.	52.	44.	10.	19.
2	54.	48.	58.	18.	42.	33.	70.	15.
3	13.	9.	38.	38.	45.	45.	32.	62.
4	5.	28.	56.	52.	11.	60.	60.	12.
5	55.	17.	21.	32.	49.	23.	69.	10.
6	51.	12.	64.	40.	20.	19.	20.	63.
7	67.	46.	32.	37.	64.	3.	19.	49.
8	30.	30.	41.	57.	26.	22.	44.	27.
9	19.	37.	25.	27.	17.	21.	68.	13.
10	39.	64.	67.	11.	9.	38.	45.	38.
11	35.	23.	39.	44.	23.	7.	11.	3.
12	25.	24.	45.	69.	47.	4.	40.	39.
13	4.	40.	30.	29.	14.	34.	35.	45.
14	50.	60.	20.	3.	57.	16.	63.	68.
15	29.	62.	53.	19.	32.	6.	43.	24.
16	62.	69.	37.	35.	67.	59.	22.	57.
17	12.	67.	70.	30.	2.	50.	56.	20.
18	9.	43.	50.	58.	66.	15.	62.	1.
19	3.	21.	15.	56.	34.	64.	39.	50.
20	6.	39.	12.	15.	6.	20.	61.	61.
21	21.	8.	68.	4.	68.	47.	51.	47.
22	43.	19.	11.	17.	63.	41.	34.	36.
23	34.	49.	51.	16.	70.	18.	2.	59.
24	8.	15.	27.	34.	56.	1.	58.	5.
25	11.	18.	55.	13.	33.	66.	36.	65.
26	56.	63.	69.	31.	38.	61.	33.	52.
27	48.	29.	65.	49.	55.	17.	17.	25.
28	38.	32.	42.	39.	15.	31.	18.	17.
29	41.	1.	14.	5.	30.	57.	64.	42.
30	69.	45.	19.	12.	41.	11.	24.	6.
31	68.	36.	28.	45.	19.	13.	66.	69.
32	45.	52.	16.	22.	16.	63.	13.	8.
33	1.	53.	33.	21.	21.	9.	4.	30.
34	61.	20.	40.	26.	51.	70.	41.	23.
35	57.	22.	9.	43.	1.	36.	5.	22.
36	33.	10.	47.	28.	24.	2.	25.	56.
37	52.	2.	34.	60.	43.	69.	57.	53.
38	7.	58.	8.	2.	58.	55.	7.	29.
39	22.	11.	3.	54.	53.	43.	30.	7.
40	28.	14.	5.	50.	35.	27.	54.	44.
41	24.	25.	49.	64.	31.	14.	31.	60.
42	27.	5.	60.	61.	29.	35.	50.	34.
43	47.	31.	66.	14.	27.	26.	14.	43.
44	70.	42.	26.	10.	13.	54.	42.	2.
45	23.	13.	57.	65.	61.	42.	29.	37.
46	40.	44.	61.	68.	69.	62.	47.	46.
47	16.	61.	52.	42.	48.	65.	59.	14.
48	18.	4.	59.	25.	60.	39.	1.	9.
49	60.	56.	17.	66.	22.	30.	52.	33.
50	14.	51.	22.	23.	59.	48.	6.	4.
51	20.	27.	24.	51.	8.	53.	12.	51.
52	2.	55.	36.	33.	37.	37.	65.	31.
53	58.	3.	54.	47.	3.	32.	37.	54.
54	63.	41.	44.	24.	50.	12.	8.	16.
55	59.	38.	46.	20.	39.	28.	49.	11.
56	66.	33.	48.	9.	12.	40.	28.	18.
57	31.	57.	10.	7.	40.	29.	55.	32.
58	64.	59.	7.	70.	46.	5.	67.	58.
59	46.	65.	43.	59.	18.	49.	26.	28.
60	17.	68.	29.	67.	5.	52.	27.	64.
61	15.	54.	1.	55.	25.	10.	9.	55.
62	65.	26.	62.	63.	44.	56.	15.	41.
63	36.	16.	31.	8.	4.	8.	21.	48.
64	26.	47.	23.	62.	28.	46.	38.	21.
65	53.	7.	2.	36.	54.	67.	23.	67.
66	42.	50.	4.	48.	65.	58.	46.	26.
67	10.	66.	35.	1.	62.	24.	53.	70.
68	37.	34.	63.	46.	36.	25.	3.	66.
69	49.	70.	13.	53.	10.	68.	16.	40.
70	44.	6.	18.	6.	7.	51.	48.	35.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(9)	X(10)	X(11)	X(12)	X(13)	X(14)	X(15)	X(16)
1	1.	49.	35.	52.	15.	4.	25.	67.
2	2.	38.	69.	60.	38.	15.	1.	26.
3	34.	65.	8.	35.	41.	6.	13.	7.
4	24.	41.	22.	2.	11.	9.	42.	25.
5	13.	15.	39.	3.	64.	50.	47.	29.
6	8.	50.	70.	56.	36.	46.	40.	35.
7	29.	6.	27.	46.	4.	61.	55.	23.
8	7.	26.	49.	70.	3.	15.	44.	10.
9	45.	18.	57.	22.	53.	55.	68.	18.
10	51.	13.	23.	18.	25.	1.	52.	22.
11	25.	52.	28.	9.	7.	65.	9.	36.
12	41.	58.	11.	54.	9.	46.	70.	49.
13	21.	3.	5.	63.	14.	50.	3.	38.
14	56.	55.	26.	29.	5.	33.	30.	64.
15	57.	44.	31.	26.	62.	33.	27.	59.
16	68.	22.	16.	44.	42.	33.	48.	1.
17	27.	10.	29.	43.	27.	69.	31.	54.
18	44.	14.	50.	21.	51.	8.	60.	4.
19	46.	53.	32.	40.	63.	67.	21.	27.
20	18.	59.	56.	42.	12.	33.	64.	14.
21	65.	24.	54.	25.	16.	15.	62.	50.
22	17.	32.	37.	10.	37.	15.	63.	30.
23	6.	37.	34.	7.	70.	47.	5.	33.
24	35.	23.	1.	67.	58.	33.	17.	28.
25	14.	46.	9.	8.	52.	33.	67.	37.
26	5.	16.	24.	45.	69.	33.	19.	46.
27	62.	25.	58.	15.	17.	33.	7.	69.
28	23.	29.	62.	5.	34.	15.	18.	56.
29	67.	43.	15.	37.	32.	33.	53.	68.
30	52.	27.	13.	61.	43.	61.	29.	17.
31	37.	5.	6.	13.	6.	57.	45.	55.
32	11.	42.	4.	53.	26.	15.	61.	63.
33	55.	11.	25.	4.	35.	54.	49.	51.
34	26.	45.	47.	55.	47.	33.	39.	32.
35	22.	9.	61.	66.	24.	15.	37.	19.
36	48.	17.	17.	59.	55.	33.	43.	16.
37	69.	8.	67.	32.	29.	61.	11.	5.
38	58.	7.	43.	19.	61.	33.	20.	40.
39	63.	19.	40.	38.	22.	33.	28.	13.
40	3.	70.	63.	16.	8.	20.	23.	3.
41	20.	30.	59.	1.	21.	33.	54.	66.
42	15.	1.	48.	58.	65.	61.	66.	65.
43	31.	56.	44.	23.	31.	6.	33.	9.
44	30.	36.	65.	33.	60.	33.	50.	62.
45	4.	33.	12.	30.	56.	56.	56.	11.
46	66.	39.	33.	31.	10.	33.	16.	60.
47	36.	35.	30.	57.	1.	54.	4.	44.
48	54.	68.	52.	69.	39.	50.	41.	61.
49	64.	51.	2.	12.	50.	6.	22.	43.
50	42.	12.	19.	27.	2.	50.	38.	42.
51	28.	2.	14.	20.	28.	15.	8.	21.
52	60.	64.	53.	62.	68.	33.	26.	31.
53	61.	66.	3.	24.	66.	50.	10.	39.
54	19.	61.	21.	47.	44.	69.	65.	12.
55	59.	69.	41.	34.	19.	33.	58.	20.
56	70.	20.	60.	11.	48.	15.	32.	6.
57	32.	34.	20.	68.	49.	33.	14.	53.
58	16.	28.	46.	41.	57.	33.	12.	48.
59	33.	62.	7.	50.	54.	4.	69.	52.
60	50.	40.	64.	64.	67.	33.	35.	45.
61	47.	31.	68.	28.	59.	15.	51.	34.
62	43.	63.	10.	36.	30.	33.	15.	8.
63	10.	60.	45.	14.	45.	61.	2.	47.
64	49.	67.	51.	39.	40.	66.	46.	70.
65	53.	4.	38.	48.	46.	33.	57.	57.
66	39.	48.	42.	17.	33.	33.	6.	58.
67	9.	57.	55.	51.	23.	61.	34.	15.
68	38.	21.	66.	65.	18.	2.	36.	41.
69	40.	54.	36.	6.	13.	69.	59.	2.
70	12.	47.	18.	49.	20.	61.	24.	24.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(17)	X(18)	X(19)	X(20)	X(21)	X(22)	X(23)	X(24)
1	9.	34.	4.	23.	59.	12.	24.	12.
2	54.	42.	67.	30.	63.	57.	47.	59.
3	61.	9.	21.	8.	50.	6.	58.	37.
4	67.	47.	39.	42.	62.	65.	58.	33.
5	9.	49.	60.	7.	9.	52.	63.	12.
6	34.	9.	17.	35.	60.	15.	27.	12.
7	66.	9.	16.	48.	7.	51.	22.	49.
8	44.	50.	44.	66.	43.	67.	38.	50.
9	19.	9.	40.	50.	25.	1.	23.	12.
10	9.	51.	53.	4.	11.	54.	30.	12.
11	9.	25.	49.	52.	16.	7.	35.	38.
12	28.	54.	34.	38.	39.	3.	34.	51.
13	9.	19.	57.	45.	54.	25.	53.	56.
14	55.	44.	13.	10.	10.	16.	29.	44.
15	9.	22.	35.	59.	2.	32.	52.	62.
16	9.	35.	10.	21.	32.	69.	10.	40.
17	69.	40.	6.	24.	66.	53.	45.	27.
18	9.	9.	2.	46.	48.	28.	65.	60.
19	63.	32.	64.	32.	28.	23.	10.	63.
20	48.	60.	38.	63.	14.	66.	31.	12.
21	68.	18.	61.	43.	46.	5.	20.	43.
22	70.	52.	18.	16.	15.	64.	50.	35.
23	39.	64.	28.	67.	27.	46.	66.	66.
24	47.	31.	31.	20.	20.	35.	48.	12.
25	9.	9.	59.	55.	67.	62.	10.	34.
26	51.	9.	70.	28.	19.	13.	49.	12.
27	38.	65.	68.	62.	52.	50.	42.	12.
28	42.	9.	1.	26.	40.	44.	33.	29.
29	27.	28.	36.	40.	49.	20.	64.	30.
30	60.	37.	47.	33.	70.	17.	44.	12.
31	9.	43.	51.	61.	51.	31.	37.	52.
32	62.	70.	5.	57.	23.	10.	36.	42.
33	29.	55.	52.	22.	5.	19.	10.	12.
34	9.	68.	65.	15.	13.	26.	10.	39.
35	20.	33.	46.	12.	4.	29.	10.	12.
36	35.	41.	19.	6.	44.	68.	19.	32.
37	22.	23.	8.	49.	29.	34.	28.	12.
38	59.	9.	32.	68.	21.	39.	10.	12.
39	33.	67.	50.	70.	68.	14.	26.	45.
40	56.	9.	54.	13.	6.	18.	10.	65.
41	9.	36.	42.	60.	38.	59.	10.	26.
42	65.	56.	14.	39.	12.	47.	10.	70.
43	9.	46.	9.	41.	31.	58.	51.	57.
44	37.	39.	33.	69.	37.	43.	10.	12.
45	9.	69.	23.	31.	58.	45.	10.	25.
46	23.	53.	25.	5.	56.	24.	25.	12.
47	21.	30.	7.	34.	3.	37.	58.	64.
48	53.	9.	26.	19.	36.	70.	10.	12.
49	64.	9.	56.	27.	41.	61.	10.	36.
50	24.	9.	69.	3.	47.	41.	10.	55.
51	36.	63.	27.	18.	18.	21.	46.	47.
52	46.	62.	43.	51.	8.	30.	40.	12.
53	52.	20.	3.	54.	33.	11.	10.	12.
54	49.	61.	37.	14.	26.	33.	62.	24.
55	9.	48.	48.	37.	22.	55.	58.	58.
56	40.	66.	20.	2.	65.	2.	32.	69.
57	9.	9.	45.	56.	61.	49.	10.	68.
58	45.	57.	30.	25.	57.	48.	41.	48.
59	32.	29.	55.	65.	55.	22.	58.	67.
60	9.	21.	11.	36.	24.	27.	43.	46.
61	57.	9.	66.	9.	69.	36.	69.	31.
62	50.	9.	62.	64.	1.	9.	58.	41.
63	30.	58.	22.	17.	42.	60.	39.	61.
64	31.	9.	58.	1.	45.	40.	58.	54.
65	26.	24.	24.	11.	17.	56.	70.	12.
66	41.	38.	15.	47.	34.	38.	21.	12.
67	25.	59.	12.	29.	64.	4.	10.	28.
68	43.	45.	63.	53.	30.	8.	58.	12.
69	58.	27.	29.	58.	53.	42.	68.	12.
70	18.	26.	41.	44.	35.	63.	67.	53.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(25)	X(26)	X(27)	X(28)	X(29)	X(30)	X(31)	X(32)
1	59.	62.	23.	22.	20.	34.	59.	65.
2	18.	8.	29.	40.	28.	45.	65.	65.
3	66.	62.	20.	34.	50.	70.	44.	55.
4	66.	62.	16.	31.	58.	5.	32.	65.
5	18.	62.	19.	3.	42.	13.	23.	38.
6	18.	31.	21.	7.	60.	43.	9.	50.
7	43.	45.	10.	48.	9.	9.	55.	42.
8	18.	20.	44.	7.	19.	68.	16.	49.
9	18.	52.	4.	46.	55.	32.	70.	30.
10	37.	6.	6.	35.	51.	10.	33.	5.
11	51.	38.	24.	40.	49.	57.	30.	23.
12	18.	18.	13.	24.	25.	65.	3.	65.
13	64.	62.	11.	28.	38.	7.	8.	14.
14	69.	22.	57.	59.	54.	53.	15.	16.
15	18.	5.	7.	40.	57.	22.	24.	65.
16	39.	62.	32.	14.	44.	56.	44.	30.
17	18.	35.	55.	25.	67.	61.	44.	52.
18	60.	51.	65.	16.	13.	48.	27.	57.
19	18.	13.	43.	14.	45.	54.	58.	65.
20	18.	62.	36.	70.	10.	52.	19.	48.
21	18.	42.	49.	27.	8.	1.	20.	56.
22	54.	10.	2.	11.	47.	59.	2.	45.
23	18.	50.	30.	69.	41.	27.	12.	30.
24	18.	4.	70.	59.	7.	51.	14.	12.
25	45.	3.	42.	33.	18.	64.	44.	13.
26	44.	62.	69.	4.	3.	40.	7.	37.
27	62.	62.	26.	44.	21.	49.	53.	30.
28	18.	27.	25.	50.	1.	44.	29.	7.
29	18.	37.	53.	7.	39.	14.	26.	9.
30	18.	29.	31.	40.	65.	67.	44.	1.
31	18.	62.	63.	40.	56.	50.	25.	65.
32	18.	49.	27.	29.	14.	19.	44.	36.
33	18.	7.	33.	51.	48.	41.	57.	46.
34	18.	28.	54.	59.	6.	63.	44.	65.
35	18.	62.	56.	40.	40.	18.	6.	54.
36	65.	2.	47.	32.	30.	11.	67.	65.
37	40.	16.	8.	67.	63.	28.	5.	65.
38	18.	46.	50.	18.	22.	62.	44.	47.
39	58.	12.	37.	20.	32.	4.	18.	6.
40	18.	48.	64.	22.	59.	36.	63.	3.
41	41.	26.	41.	17.	29.	69.	44.	4.
42	47.	43.	38.	59.	17.	58.	64.	2.
43	18.	40.	67.	59.	70.	25.	13.	10.
44	70.	9.	61.	45.	66.	23.	34.	58.
45	48.	33.	58.	59.	46.	2.	21.	30.
46	18.	47.	5.	59.	15.	35.	69.	40.
47	53.	19.	68.	59.	43.	30.	44.	22.
48	18.	62.	9.	14.	61.	16.	17.	30.
49	50.	32.	18.	59.	26.	6.	22.	11.
50	18.	62.	66.	49.	69.	46.	44.	51.
51	18.	24.	12.	2.	31.	42.	44.	30.
52	63.	62.	14.	40.	62.	60.	31.	21.
53	18.	62.	62.	59.	33.	15.	44.	53.
54	61.	25.	22.	10.	36.	29.	56.	39.
55	42.	62.	59.	26.	4.	31.	66.	19.
56	57.	30.	17.	59.	11.	66.	10.	30.
57	36.	62.	1.	59.	23.	55.	4.	30.
58	52.	44.	35.	9.	53.	26.	28.	15.
59	18.	36.	34.	59.	68.	17.	61.	44.
60	18.	34.	39.	7.	24.	8.	44.	8.
61	18.	39.	60.	68.	27.	12.	60.	65.
62	55.	11.	15.	19.	37.	37.	35.	30.
63	56.	62.	48.	1.	12.	21.	44.	65.
64	49.	21.	40.	59.	16.	24.	1.	30.
65	38.	41.	46.	47.	64.	47.	44.	30.
66	18.	1.	52.	14.	52.	39.	54.	43.
67	18.	15.	28.	22.	35.	3.	44.	17.
68	67.	23.	51.	40.	34.	33.	62.	18.
69	18.	14.	45.	30.	2.	38.	11.	41.
70	46.	17.	3.	59.	5.	20.	68.	20.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(33)	X(34)	X(35)	X(36)	X(37)	X(38)	X(39)	X(40)
1	68.	37.	20.	18.	29.	24.	63.	31.
2	33.	31.	41.	37.	28.	5.	31.	54.
3	17.	19.	60.	4.	55.	15.	9.	37.
4	5.	53.	12.	47.	3.	23.	30.	66.
5	58.	20.	51.	70.	20.	53.	33.	51.
6	5.	24.	7.	27.	47.	58.	65.	15.
7	33.	16.	8.	25.	63.	29.	27.	60.
8	47.	67.	14.	30.	46.	39.	7.	69.
9	33.	22.	25.	6.	51.	6.	13.	59.
10	58.	36.	47.	43.	53.	56.	39.	52.
11	47.	66.	57.	8.	39.	10.	57.	47.
12	17.	14.	43.	67.	41.	51.	26.	28.
13	17.	17.	44.	38.	70.	69.	15.	57.
14	33.	45.	31.	65.	48.	18.	54.	26.
15	5.	57.	19.	3.	54.	27.	68.	40.
16	17.	69.	65.	28.	15.	3.	69.	50.
17	69.	35.	46.	39.	23.	49.	53.	3.
18	58.	34	63.	58.	52.	59.	43.	13.
19	64.	6.	15.	31.	34.	28.	70.	64.
20	17.	61.	62.	35.	40.	40.	34.	39.
21	33.	63.	55.	55.	61.	9.	62.	4.
22	64.	56.	23.	10.	43.	34.	11.	5.
23	47.	68.	33.	11.	31.	57.	16.	27.
24	17.	48.	9.	29.	4.	11.	61.	56.
25	58.	70.	3.	57.	60.	60.	46.	35.
26	17.	40.	59.	1.	59.	52.	22.	29.
27	64.	25.	28.	60.	42.	62.	58.	24.
28	5.	44.	22.	63.	14.	17.	38.	44.
29	33.	27.	56.	5.	25.	26.	25.	25.
30	47.	54.	48.	51.	38.	36.	48.	18.
31	17.	11.	50.	14.	2.	45.	52.	30.
32	47.	43.	6.	13.	32.	68.	64.	45.
33	33.	21.	67.	46.	33.	48.	51.	17.
34	17.	18.	38.	59.	67.	35.	29.	34.
35	70.	59.	49.	17.	26.	16.	10.	41.
36	58.	13.	36.	20.	45.	67.	24.	22.
37	47.	42.	53.	32.	17.	54.	17.	11.
38	33.	2.	27.	62.	12.	61.	23.	62.
39	17.	47.	26.	12.	68.	21.	55.	33.
40	33.	38.	40.	50.	37.	70.	60.	14.
41	33.	9.	58.	9.	36.	22.	6.	65.
42	33.	51.	30.	16.	19.	19.	14.	16.
43	33.	1.	1.	21.	69.	12.	42.	42.
44	5.	46.	16.	54.	30.	42.	36.	53.
45	33.	7.	39.	26.	9.	1.	40.	23.
46	17.	30.	2.	19.	50.	47.	21.	43.
47	47.	28.	61.	49.	65.	41.	37.	58.
48	17.	15.	70.	22.	13.	64.	56.	63.
49	47.	4.	45.	23.	57.	30.	35.	20.
50	17.	65.	4.	41.	22.	32.	3.	6.
51	5.	39.	13.	66.	24.	7.	47.	12.
52	33.	32.	5.	34.	35.	31.	28.	8.
53	47.	55.	54.	69.	62.	43.	12.	55.
54	5.	12.	32.	68.	49.	33.	2.	46.
55	47.	10.	10.	2.	6.	65.	44.	9.
56	17.	29.	52.	15.	8.	66.	50.	68.
57	64.	3.	29.	64.	10.	13.	20.	1.
58	33.	64.	35.	53.	66.	55.	67.	49.
59	58.	60.	68.	52.	56.	20.	8.	48.
60	5.	50.	21.	44.	7.	37.	18.	7.
61	33.	52.	24.	33.	27.	63.	32.	32.
62	68.	58.	11.	56.	1.	50.	19.	38.
63	58.	62.	18.	40.	64.	2.	4.	36.
64	47.	41.	37.	42.	16.	14.	41.	61.
65	47.	23.	17.	48.	44.	25.	49.	67.
66	17.	33.	69.	7.	18.	44.	1.	10.
67	64.	49.	34.	36.	5.	46.	5.	70.
68	47.	8.	66.	61.	11.	4.	59.	21.
69	58.	5.	42.	24.	58.	8.	45.	19.
70	5.	26.	64.	45.	21.	38.	66.	2.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (continued)

RUN NO.	X(41)	X(42)	X(43)	X(44)	X(45)	X(46)	X(47)	X(48)
1	11.	57.	69.	43.	21.	42.	34.	32.
2	1.	31.	22.	26.	15.	14.	22.	15.
3	25.	9.	29.	18.	9.	9.	4.	43.
4	59.	43.	46.	15.	60.	64.	11.	21.
5	43.	63.	45.	11.	1.	17.	54.	11.
6	44.	58.	5.	34.	22.	70.	63.	12.
7	53.	5.	65.	37.	2.	37.	52.	16.
8	57.	45.	43.	13.	55.	29.	51.	24.
9	35.	64.	12.	67.	67.	56.	36.	13.
10	17.	29.	27.	40.	61.	57.	15.	51.
11	5.	32.	3.	14.	52.	12.	61.	60.
12	14.	44.	56.	53.	37.	39.	1.	6.
13	41.	54.	18.	66.	12.	34.	49.	28.
14	22.	47.	58.	4.	35.	19.	68.	31.
15	55.	17.	51.	25.	53.	15.	7.	67.
16	21.	30.	17.	47.	14.	68.	43.	39.
17	20.	66.	63.	58.	44.	20.	58.	64.
18	69.	12.	19.	24.	58.	25.	46.	59.
19	64.	62.	39.	41.	31.	32.	55.	54.
20	28.	56	30.	28.	17.	51.	27.	44.
21	24.	13.	34.	70.	33.	23.	47.	41.
22	10.	69.	23.	55.	41.	2.	66.	22.
23	54.	61.	21.	68.	68.	49.	37.	7.
24	15.	49.	40.	49.	34.	59.	57.	68.
25	39.	28.	48.	45.	11.	11.	2.	49.
26	51.	48.	60.	1.	47.	31.	29.	42.
27	42.	2.	26.	44.	27.	36.	33.	66.
28	56.	65.	15.	17.	50.	7.	14.	20.
29	4.	11.	16.	54.	51.	65.	31.	50.
30	67.	20.	7.	21.	18.	8.	6.	3.
31	58.	36.	8.	50.	48.	3.	19.	35.
32	48.	19.	1.	23.	7.	47.	42.	55.
33	23.	39.	57.	3.	13.	60.	20.	2.
34	47.	46.	9.	57.	64.	50.	65.	29.
35	61.	18.	68.	62.	45.	5.	10.	63.
36	26.	25.	2.	9.	56.	43.	64.	1.
37	16.	37.	6.	10.	3.	52.	25.	69.
38	3.	53.	44.	46.	16.	10.	13.	57.
39	34.	68.	66	5.	36.	30.	44.	27.
40	40.	16.	20.	8.	62.	26.	30.	58.
41	29.	10.	28.	60.	39.	45.	70.	46.
42	32.	27.	52.	12.	19.	67.	3.	52.
43	46.	40.	62.	36.	6.	48.	28.	61.
44	37.	8.	37.	20.	43.	22.	40.	9.
45	12.	4.	35.	31.	25.	4.	35.	8.
46	50.	52.	53.	6.	63.	6.	48.	47.
47	8.	24.	13.	59.	26.	24.	5.	4.
48	19.	14.	54.	30.	66.	16.	21.	19.
49	52.	60.	11.	61.	40.	21.	17.	53.
50	33.	55.	42.	51.	42.	58.	53.	23.
51	60.	1.	33.	29.	49.	54.	59.	34.
52	66.	3.	47.	64.	28.	18.	50.	5.
53	31.	59.	64.	35.	59.	53.	60.	17.
54	30.	51.	25.	52.	57.	35.	16.	70.
55	36.	67.	50.	33.	24.	44.	24.	18.
56	27.	21.	67.	56.	20.	40.	56.	33.
57	18.	23.	36.	2.	69.	66.	38.	48.
58	6.	35.	61.	69.	54.	61.	8.	38.
59	38.	34.	49.	7.	5.	28.	69.	65.
60	2.	38.	24.	48.	23.	1.	62.	36.
61	7.	6.	31.	38.	29.	55.	32.	56.
62	9.	22.	55.	42.	32.	63.	41.	10.
63	49.	50	14.	27.	8.	41.	9.	25.
64	68.	33.	10.	32.	4.	46.	45.	26.
65	45.	41.	41.	16.	70.	33.	23.	30.
66	70.	42.	59.	65.	10.	69.	18.	45.
67	62.	15.	32.	19.	46.	27.	39.	62.
68	65.	70.	4.	39.	30.	38.	12.	37.
69	13.	7.	38.	22.	65.	62.	26.	14.
70	63.	26.	70.	63.	38.	13.	67.	40.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-3b. RANKS* OF LATIN HYPERCUBE SAMPLE INPUT VECTORS MULTIPLE INTRUSION SCENARIO (concluded)

RUN NO.	X(49)	X(50)	X(51)
1	14.	33.	63.
2	40.	54.	30.
3	58.	64.	60.
4	6.	11.	55.
5	56.	44.	56.
6	67.	39.	27.
7	2.	17.	21.
8	60.	66.	43.
9	17.	27.	24.
10	23.	23.	66.
11	62.	5.	62.
12	52.	1.	9.
13	43.	45.	61.
14	9.	19.	51.
15	19.	57.	37.
16	[illegible]	56.	22.
17	44.	16.	10.
18	10.	35.	28.
19	8.	50.	57.
20	13.	30.	44.
21	70.	22.	70.
22	11.	61.	11.
23	31.	6.	48.
24	37.	8.	40.
25	20	26.	35.
26	25.	24.	2.
27	12.	65.	39.
28	48.	70.	19.
29	3.	58.	1.
30	4.	10.	59.
31	24.	63.	65.
32	55.	52.	18.
33	36.	69.	5.
34	1.	31.	52.
35	57.	38.	33.
36	53.	37.	58.
37	21.	9.	8.
38	63.	4.	25.
39	22.	60.	46.
40	42.	15.	34.
41	46.	25.	31.
42	47.	42.	68.
43	18.	51.	54.
44	65.	21.	41.
45	38.	40.	7.
46	59.	14.	26.
47	34.	43.	16.
48	7.	20.	50.
49	64.	18.	3.
50	27.	62.	20.
51	16.	3.	17.
52	66.	55.	15.
53	30.	68.	45.
54	54.	67.	49.
55	49.	13.	42.
56	35.	29.	32.
57	33.	48.	53.
58	29.	53.	12.
59	45.	7.	23.
60	5.	28.	69.
61	26.	47.	29.
62	32.	59.	38.
63	28.	2.	14.
64	51.	46.	47.
65	69.	12.	36.
66	39.	34.	67.
67	41.	49.	13.
68	15.	36.	6.
69	50.	41.	64.
70	68.	32.	4.

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* Rank refers to relative position of the sampled value within the assigned range of values. For example, a rank of 1 indicates that the corresponding value in Table C-3a is the smallest value sampled for that parameter.

TABLE C-4. SUMMARY OF MULTIPLE INTRUSION SAMPLES

Vector No.	Number of Holes	Number of Panels	Number of Holes in Brine Pocket	Number of Panels Whose Penetration Pattern Most Resembles:		
				E1	E2	E1E2
1	7	5	0	0	5	0
2	3	3	0	0	3	0
3	2	2	1	1	1	0
4	1	1	0	0	1	0
5	5	5	2	2	3	0
6	1	1	1	1	0	0
7	3	3	1	1	2	0
8	4	4	0	0	4	0
9	3	2	1	1	1	0
10	5	5	0	0	5	0
11	4	4	3	3	1	0
12	2	1	1	0	0	1
13	2	2	1	1	1	0
14	3	3	1	1	2	0
15	1	1	1	1	0	0
16	2	2	1	1	1	0
17	8	5	0	0	5	0
18	5	3	0	0	3	0
19	6	3	0	0	3	0
20	2	1	0	0	1	0
21	3	2	0	0	2	0
22	6	5	2	1	3	1
23	4	3	1	1	2	0
24	2	2	1	1	1	0
25	5	3	4	2	0	1
26	2	2	1	1	1	0
27	6	4	0	0	4	0
28	1	1	0	0	1	0
29	3	2	2	1	1	0
30	4	3	1	1	2	0
31	2	2	1	1	1	0
32	4	4	1	1	3	0
33	3	3	2	2	1	0
34	2	2	1	1	1	0
35	9	6	2	2	4	0
36	5	5	2	2	3	0
37	4	3	3	2	0	1
38	3	3	0	0	3	0
39	2	2	1	1	1	0
40	3	3	0	0	3	0

TABLE C-4. SUMMARY OF MULTIPLE INTRUSION SAMPLES (concluded)

Vector No.	Number of Holes	Number of Panels	Number of Holes in Brine Pocket	Number of Panels Whose Penetration Pattern Most Resembles:		
				E1	E2	E1E2
41	3	3	1	1	2	0
42	3	3	2	2	1	0
43	3	3	1	1	2	0
44	1	1	0	0	1	0
45	3	3	1	1	2	0
46	2	2	1	1	1	0
47	4	4	1	1	3	0
48	2	2	1	1	1	0
49	4	4	1	1	3	0
50	2	2	1	1	1	0
51	1	1	0	0	1	0
52	3	3	0	0	3	0
53	4	3	1	0	2	1
54	1	1	1	1	0	0
55	4	4	1	1	3	0
56	2	2	0	0	2	0
57	6	4	2	2	2	0
58	3	2	1	1	1	0
59	5	4	1	0	3	1
60	1	1	0	0	1	0
61	3	2	0	0	2	0
62	7	6	1	1	5	0
63	5	4	3	2	2	0
64	4	4	2	2	2	0
65	4	4	0	0	4	0
66	2	2	0	0	2	0
67	6	5	0	0	5	0
68	4	4	1	1	3	0
69	5	4	0	0	4	0
70	1	1	0	0	1	0
Total	238	204	63	54	144	6
Average	3.40	2.91	0.90	0.77	2.06	0.09

Miscellaneous statistics:

Average holes/panel = 238/204 = 1.17

P(hole hits pocket) = 63/238 = 0.26

$\frac{\text{\# rooms over pocket}}{\text{total \# of rooms}}$ = 42/144 = 0.29

P(E1) = 54/204 = 0.26
P(E2) = 144/204 = 0.706
P(E1E2-like) = 6/204 = 0.03

TABLE C-5. SAMPLED VALUES FOR THE UNDISTURBED PERFORMANCE SCENARIO (Marietta et al., 1989)

Parameters

x(1)	nuclide solubility (molar)
x(2)	pressure (Pa) driving flow through the repository
x(3)	repository hydraulic conductivity (m/s)
x(4)	MB139 seal hydraulic conductivity (m/s)
x(5)	MB139 seal porosity
x(6)	plutonium and thorium retardations in MB139
x(7)	americium retardation in MB139
x(8)	lower-shaft seal hydraulic conductivity (m/s)
x(9)	lower-shaft seal porosity
x(10)	plutonium, thorium, and americium retardations in the lower shaft seal
x(11)	neptunium retardation in the lower shaft seal
x(12)	upper shaft seal hydraulic conductivity (m/s)
x(13)	upper shaft seal porosity
x(14)	plutonium, thorium, and americium retardations in the upper shaft seal

TABLE C-5. SAMPLED VALUES FOR THE UNDISTURBED PERFORMANCE SCENARIO

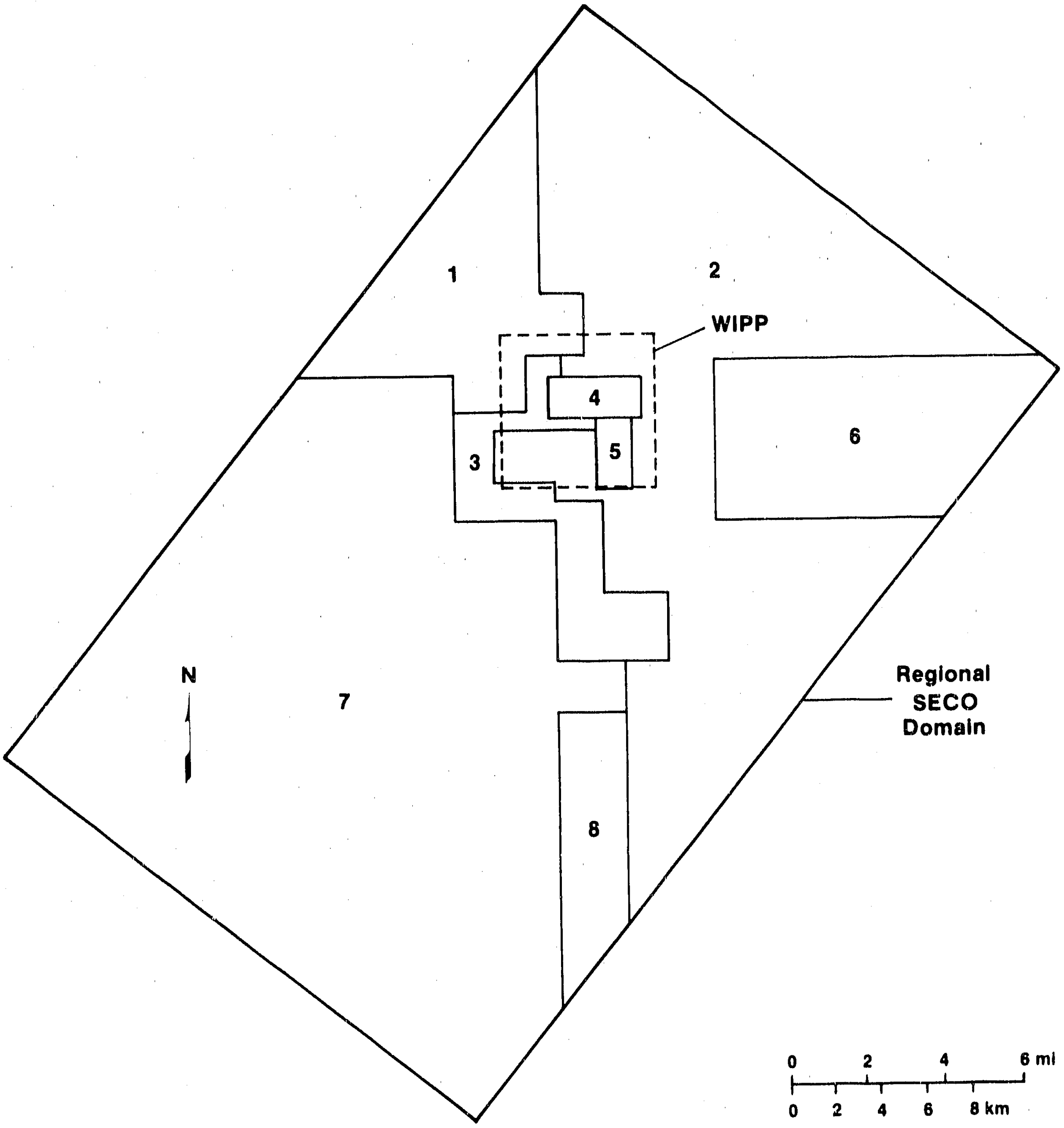
Simulation	x(1)	x(2)	x(3)	x(4)	x(5)	x(6)	x(7)
1	3.840×10^{-7}	7.726×10^{6}	3.709×10^{-8}	6.188×10^{-12}	3.351×10^{-2}	5.56	1.67
2	3.766×10^{-6}	1.135×10^{7}	3.741×10^{-8}	2.067×10^{-11}	2.704×10^{-2}	2.92	2.00
3	5.746×10^{-9}	7.356×10^{6}	8.721×10^{-9}	1.029×10^{-11}	2.634×10^{-2}	3.59	1.91
4	1.862×10^{-7}	6.472×10^{6}	1.245×10^{-7}	1.258×10^{-11}	2.644×10^{-2}	6.20	1.89
5	3.064×10^{-6}	6.135×10^{6}	7.494×10^{-8}	6.956×10^{-12}	3.146×10^{-2}	6.02	1.22
6	2.164×10^{-8}	1.372×10^{7}	1.116×10^{-8}	3.411×10^{-11}	2.620×10^{-2}	7.09	1.94
7	2.294×10^{-7}	1.438×10^{7}	8.761×10^{-8}	2.387×10^{-11}	3.028×10^{-2}	3.61	1.62
8	2.634×10^{-5}	9.184×10^{6}	6.730×10^{-8}	1.369×10^{-11}	2.936×10^{-2}	6.00	1.88
9	2.170×10^{-6}	9.545×10^{6}	1.155×10^{-7}	9.793×10^{-12}	3.322×10^{-2}	5.06	1.85
10	2.650×10^{-7}	9.079×10^{6}	8.248×10^{-8}	1.415×10^{-11}	2.605×10^{-2}	6.02	2.36
11	3.976×10^{-6}	7.331×10^{6}	2.084×10^{-7}	1.548×10^{-11}	2.845×10^{-2}	4.88	2.06
12	3.956×10^{-9}	1.123×10^{7}	3.611×10^{-8}	1.038×10^{-11}	2.878×10^{-2}	5.46	2.67
13	3.142×10^{-7}	7.870×10^{6}	8.955×10^{-8}	3.502×10^{-11}	2.701×10^{-2}	4.66	2.45
14	1.777×10^{-5}	1.017×10^{7}	1.008×10^{-7}	1.389×10^{-11}	3.338×10^{-2}	4.56	1.12
15	8.686×10^{-5}	8.090×10^{6}	1.224×10^{-7}	3.942×10^{-11}	2.433×10^{-2}	3.24	1.38
16	3.621×10^{-9}	1.419×10^{7}	1.853×10^{-7}	3.996×10^{-11}	3.615×10^{-2}	4.34	2.08
17	1.052×10^{-8}	1.212×10^{7}	5.931×10^{-8}	1.650×10^{-11}	2.856×10^{-2}	5.94	1.31
18	1.248×10^{-5}	1.328×10^{7}	3.305×10^{-7}	6.764×10^{-12}	3.290×10^{-2}	5.24	1.77
19	4.779×10^{-5}	1.495×10^{7}	9.050×10^{-8}	1.272×10^{-11}	3.020×10^{-2}	4.59	1.31
20	9.886×10^{-4}	9.244×10^{6}	4.670×10^{-9}	2.756×10^{-11}	3.359×10^{-2}	4.47	1.28
21	1.363×10^{-9}	6.817×10^{6}	3.943×10^{-8}	2.527×10^{-11}	3.444×10^{-2}	3.99	1.73
22	2.996×10^{-4}	1.398×10^{7}	8.365×10^{-8}	2.479×10^{-11}	3.210×10^{-2}	5.44	2.23
23	1.975×10^{-5}	7.952×10^{6}	5.282×10^{-8}	1.583×10^{-11}	3.060×10^{-2}	3.98	1.09
24	5.260×10^{-5}	8.795×10^{6}	1.552×10^{-7}	2.974×10^{-11}	3.108×10^{-2}	2.54	2.19
25	5.975×10^{-5}	1.318×10^{7}	9.950×10^{-9}	5.270×10^{-11}	3.528×10^{-2}	5.97	1.95
26	3.075×10^{-6}	1.206×10^{7}	2.415×10^{-7}	7.370×10^{-12}	3.323×10^{-2}	3.37	1.87
27	3.278×10^{-8}	1.168×10^{7}	5.018×10^{-8}	1.029×10^{-11}	3.746×10^{-2}	7.76	2.85
28	4.592×10^{-4}	8.895×10^{6}	3.924×10^{-8}	8.140×10^{-11}	2.769×10^{-2}	3.33	1.40
29	2.362×10^{-5}	9.494×10^{6}	8.909×10^{-9}	2.487×10^{-11}	3.201×10^{-2}	5.08	1.96
30	8.282×10^{-5}	1.381×10^{7}	1.401×10^{-7}	1.991×10^{-11}	3.004×10^{-2}	4.43	1.52
31	1.065×10^{-6}	1.454×10^{7}	2.917×10^{-8}	3.647×10^{-11}	3.077×10^{-2}	3.45	1.22
32	5.979×10^{-9}	1.396×10^{7}	1.098×10^{-7}	3.129×10^{-11}	2.717×10^{-2}	6.05	3.39
33	9.885×10^{-5}	1.015×10^{7}	1.345×10^{-7}	5.228×10^{-12}	3.104×10^{-2}	5.06	1.68
34	8.736×10^{-7}	1.227×10^{7}	1.467×10^{-7}	4.036×10^{-11}	3.044×10^{-2}	6.05	1.58
35	4.700×10^{-5}	9.754×10^{6}	1.126×10^{-7}	1.996×10^{-11}	3.385×10^{-2}	2.56	2.13
36	2.308×10^{-7}	9.439×10^{6}	2.966×10^{-8}	4.006×10^{-11}	3.248×10^{-2}	4.79	2.26
37	1.302×10^{-7}	9.068×10^{6}	1.029×10^{-8}	1.564×10^{-11}	3.127×10^{-2}	5.01	2.13
38	4.049×10^{-5}	1.041×10^{7}	1.031×10^{-7}	1.353×10^{-11}	3.349×10^{-2}	1.47	2.94
39	8.677×10^{-4}	8.706×10^{6}	1.475×10^{-7}	1.076×10^{-11}	2.851×10^{-2}	2.90	1.30
40	1.387×10^{-6}	1.428×10^{7}	1.074×10^{-7}	2.179×10^{-11}	3.143×10^{-2}	3.50	1.88
41	7.520×10^{-6}	6.017×10^{6}	5.639×10^{-8}	5.932×10^{-12}	3.014×10^{-2}	6.31	1.73
42	3.308×10^{-6}	1.487×10^{7}	7.924×10^{-8}	2.339×10^{-11}	2.642×10^{-2}	3.13	1.31
43	3.603×10^{-4}	1.452×10^{7}	1.015×10^{-7}	2.752×10^{-11}	3.009×10^{-2}	4.74	1.32
44	5.508×10^{-5}	1.388×10^{7}	1.421×10^{-7}	4.659×10^{-12}	2.524×10^{-2}	2.38	1.27
45	8.441×10^{-9}	7.078×10^{6}	1.150×10^{-7}	6.239×10^{-12}	2.833×10^{-2}	4.02	1.81
46	3.514×10^{-5}	1.390×10^{7}	6.470×10^{-8}	1.366×10^{-11}	2.428×10^{-2}	4.10	3.01
47	1.219×10^{-5}	6.382×10^{6}	4.751×10^{-8}	2.997×10^{-11}	2.795×10^{-2}	2.76	1.39
48	1.607×10^{-6}	1.031×10^{7}	4.650×10^{-8}	2.116×10^{-11}	2.382×10^{-2}	3.47	2.57
49	1.050×10^{-4}	1.042×10^{7}	1.543×10^{-7}	4.238×10^{-11}	2.889×10^{-2}	6.49	1.83
50	1.756×10^{-9}	8.316×10^{6}	3.608×10^{-8}	1.538×10^{-11}	2.782×10^{-2}	4.46	1.99

Source: Marietta et al., 1989

TABLE C-5. SAMPLED VALUES FOR THE UNDISTURBED PERFORMANCE SCENARIO (concluded)

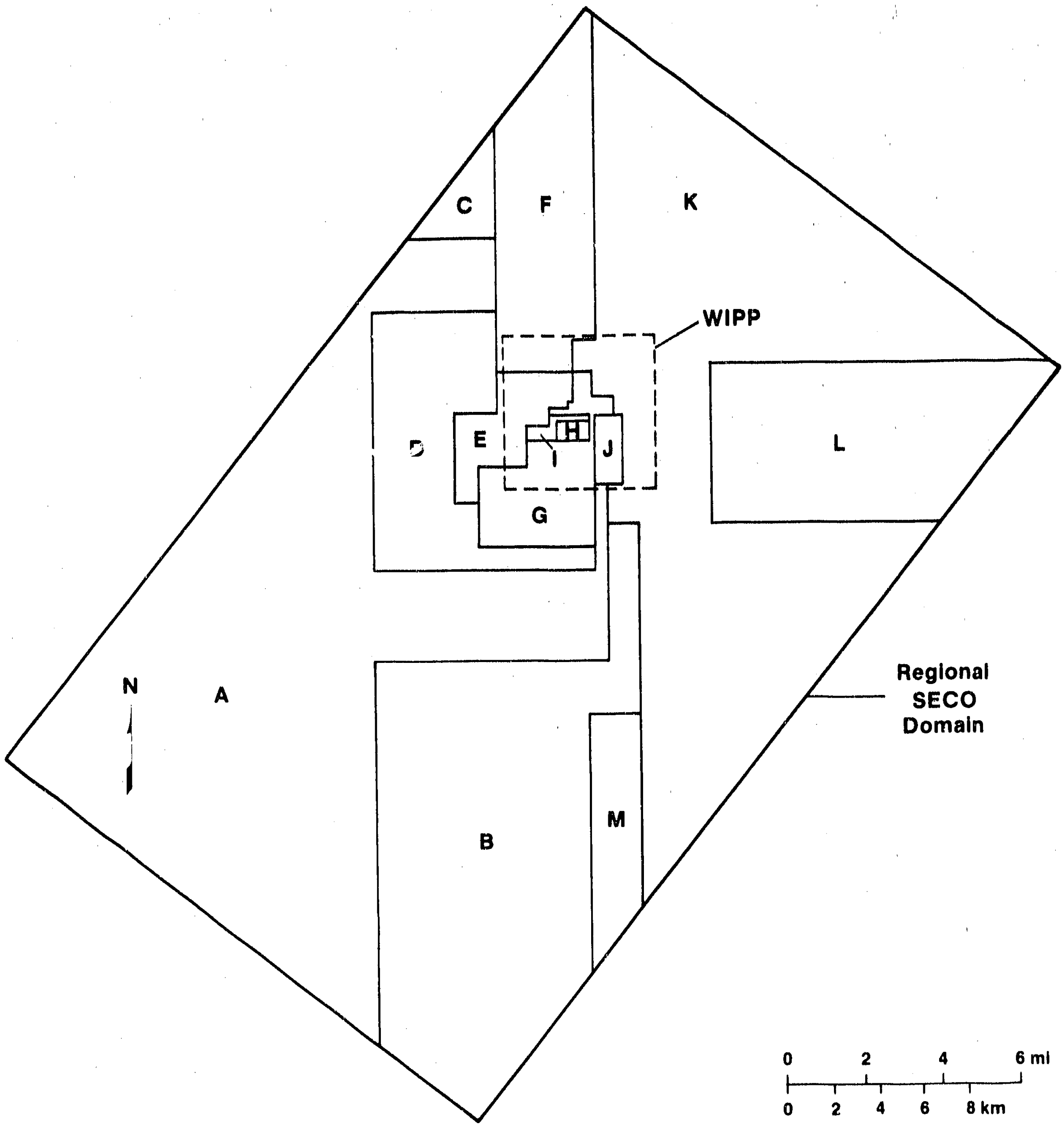
Simulation	x(8)	x(9)	x(10)	x(11)	x(12)	x(13)	x(14)
1	1.234×10^{-12}	4.559×10^{-2}	6.26	1.74	1.146×10^{-6}	0.183	2.70
2	2.584×10^{-13}	4.276×10^{-2}	5.57	1.73	3.709×10^{-5}	0.224	1.49
3	1.479×10^{-12}	4.865×10^{-2}	3.76	1.05	1.461×10^{-5}	0.173	1.56
4	1.866×10^{-13}	5.367×10^{-2}	4.97	1.08	4.560×10^{-5}	0.169	2.84
5	2.737×10^{-13}	5.301×10^{-2}	1.90	1.23	4.018×10^{-6}	0.162	1.15
6	1.610×10^{-12}	5.012×10^{-2}	5.91	1.35	7.056×10^{-7}	0.250	2.22
7	2.493×10^{-13}	5.410×10^{-2}	7.20	1.38	7.971×10^{-6}	0.197	1.13
8	2.269×10^{-13}	5.858×10^{-2}	7.52	2.87	4.784×10^{-6}	0.167	1.19
9	3.409×10^{-13}	4.994×10^{-2}	6.94	1.11	4.558×10^{-7}	0.174	1.11
10	1.028×10^{-12}	5.321×10^{-2}	5.51	1.43	8.351×10^{-5}	0.252	1.54
11	4.320×10^{-13}	4.280×10^{-2}	6.57	1.23	1.362×10^{-6}	0.184	1.50
12	1.430×10^{-12}	4.590×10^{-2}	8.01	1.30	3.592×10^{-6}	0.160	2.05
13	7.117×10^{-13}	4.071×10^{-2}	6.40	1.03	9.098×10^{-7}	0.207	1.27
14	1.294×10^{-12}	5.168×10^{-2}	6.46	1.75	8.554×10^{-6}	0.219	1.28
15	1.712×10^{-12}	4.085×10^{-2}	2.17	1.52	3.958×10^{-5}	0.140	1.14
16	7.330×10^{-13}	5.422×10^{-2}	6.57	1.62	4.618×10^{-5}	0.230	1.32
17	8.494×10^{-13}	4.854×10^{-2}	6.34	1.27	4.342×10^{-6}	0.203	1.42
18	2.980×10^{-13}	5.290×10^{-2}	5.81	1.53	7.251×10^{-7}	0.154	1.79
19	2.466×10^{-13}	5.396×10^{-2}	1.34	1.20	9.600×10^{-6}	0.190	1.36
20	1.469×10^{-12}	5.340×10^{-2}	5.19	2.37	4.268×10^{-5}	0.220	1.22
21	9.075×10^{-13}	4.275×10^{-2}	5.55	1.55	1.741×10^{-5}	0.180	2.30
22	2.326×10^{-12}	3.812×10^{-2}	5.29	1.73	6.944×10^{-6}	0.224	1.83
23	5.617×10^{-13}	5.365×10^{-2}	3.28	1.15	6.350×10^{-6}	0.247	1.58
24	1.245×10^{-13}	3.912×10^{-2}	6.07	1.30	4.983×10^{-6}	0.216	1.75
25	2.738×10^{-13}	5.134×10^{-2}	5.80	1.57	5.112×10^{-6}	0.173	2.13
26	4.234×10^{-13}	5.084×10^{-2}	6.12	1.29	2.229×10^{-6}	0.157	1.36
27	1.231×10^{-12}	5.447×10^{-2}	6.04	1.95	2.972×10^{-6}	0.192	1.15
28	9.053×10^{-13}	4.069×10^{-2}	4.02	1.18	2.898×10^{-5}	0.165	1.89
29	9.678×10^{-13}	5.325×10^{-2}	5.65	1.49	1.038×10^{-6}	0.241	1.83
30	3.203×10^{-13}	4.638×10^{-2}	7.01	1.57	4.231×10^{-5}	0.234	1.07
31	1.375×10^{-12}	4.566×10^{-2}	2.89	1.17	3.047×10^{-6}	0.210	2.86
32	3.295×10^{-13}	5.297×10^{-2}	6.22	1.79	9.435×10^{-6}	0.125	2.01
33	1.491×10^{-13}	5.286×10^{-2}	4.55	1.01	2.038×10^{-5}	0.216	2.30
34	3.422×10^{-13}	4.671×10^{-2}	6.67	1.22	6.236×10^{-6}	0.157	1.16
35	2.104×10^{-12}	4.903×10^{-2}	6.39	1.62	8.049×10^{-5}	0.175	1.47
36	7.322×10^{-13}	5.339×10^{-2}	5.43	1.28	1.424×10^{-5}	0.223	1.04
37	9.451×10^{-13}	6.109×10^{-2}	7.72	1.36	2.760×10^{-5}	0.205	2.86
38	7.042×10^{-13}	5.316×10^{-2}	8.13	1.10	3.642×10^{-5}	0.190	1.11
39	4.705×10^{-13}	5.162×10^{-2}	6.12	1.24	8.713×10^{-5}	0.164	1.04
40	2.980×10^{-13}	5.946×10^{-2}	6.59	1.13	1.798×10^{-5}	0.165	2.63
41	7.457×10^{-13}	5.566×10^{-2}	7.15	1.82	1.707×10^{-5}	0.186	1.08
42	4.032×10^{-13}	5.356×10^{-2}	4.76	1.14	9.796×10^{-6}	0.199	1.21
43	5.682×10^{-12}	4.538×10^{-2}	2.28	1.63	6.856×10^{-6}	0.192	1.32
44	4.052×10^{-13}	5.742×10^{-2}	5.63	1.26	3.338×10^{-5}	0.183	2.43
45	4.843×10^{-13}	4.845×10^{-2}	5.00	1.21	1.838×10^{-5}	0.229	1.75
46	2.171×10^{-12}	5.598×10^{-2}	6.90	1.43	3.949×10^{-6}	0.196	1.85
47	6.854×10^{-13}	5.543×10^{-2}	4.84	1.22	9.012×10^{-5}	0.260	1.63
48	9.609×10^{-13}	5.179×10^{-2}	3.76	1.88	5.632×10^{-5}	0.206	1.10
49	2.143×10^{-13}	4.907×10^{-2}	7.04	1.43	3.919×10^{-6}	0.204	2.80
50	1.755×10^{-13}	5.480×10^{-2}	2.83	1.92	4.146×10^{-6}	0.239	2.17

Source: Marietta et al., 1989



TRI-6342-785-1

Figure C-1. Hydraulic Conductivity Zones Determined Without Pilot Points.



TRI-6342-786-1

Figure C-2. Hydraulic Conductivity Zones Determined With Pilot Points.

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APPENDIX D:
RESPONSE TO REVIEW COMMENTS

APPENDIX D: RESPONSE TO REVIEW COMMENTS

Response to Comments from
New Mexico Environmental Improvement Division
on SAND89-2027

Performance Assessment Methodology Demonstration:
Methodology Development for Evaluating Compliance
with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant

The reviewed document will not be updated. All responses relate to SAND90-2347, the *Preliminary Comparison with 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant, December 1990*, which supersedes SAND89-2027, or to the corresponding data report.

Comment. Page III-18: "Transmissivities of $2.9*10^{-10}$ and $2.4*10^{-10}$ m^2/s should translate into $2.7*10^{-4}$ ft^2/d and $2.2*10^{-4}$ ft^2/d (in that order!)."

Response. This metrication error is corrected.

Comment. Page III-23: "An area of 12.24km*11.7km translates into an area of 7.65mi*7.3mi."

Response. This text not repeated in SAND90-2347.

Comment. Page III-27: "The compressibility value of $1.1*10^{-9}$ m^2/N seems to be on the low side. Since compressibility decreases with pressure, the question arises as to whether this measurement was taken in situ (under lithostatic pressure), and if so, how was this performed?"

Response. See Rechard, R.P., H.J. Iuzzolino, and J.S. Sandha, 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Comment. Page IV-32: "The expected value 10^{-11} m/s translates into 10^{-6} ft/d (approximately) and not 10^{-11} ft/d."

Response. This text not repeated in SAND90-2347.

Comment. Page A-17: "The first paragraph under RESULTS is not clear."

Response. See Rechard, R.P., W. Beyeler, R.D. McCurley, D.K. Rudeen, J.E. Bean, and J.D. Schreiber, 1990. *Parameter Sensitivity Studies of Selected Components of the WIPP Repository System*, SAND89-2030. Sandia National Laboratories, Albuquerque, NM. That report expands the preliminary calculations described in Appendix A of SAND89-2027.

Comment. Page E-4: "If anoxic corrosion has the potential to produce 2 moles of H_2 per drum per year for 336 years, then the total amount of H_2 produced per drum will be 672 moles/drum. If the H_2 production rate can be slowed down to last 2000 years, then this 'optimistic' estimate will yield 0.336 moles per drum per year. This is in disagreement with the listed estimate of 0.262 moles per drum per year. As a result of this difference in H_2 production rate, the following items are in disagreement:

a) Page E-5

1) The arithmetic mean: 1.17 moles per drum per year instead of 1.13 (1st and 6th line Page E-5, 5th line Page E-6)

2) 512 years of anoxic corrosion instead of 529 years

3) Correction from 512 years to 510 years instead of 529 years to 527 years.

b) Page E-6

1) 1.75 moles/drums/year instead of 1.70 (6th and 30th line)

2) 2.60 moles/drums/year instead of 2.55."

Response. See Rechard, R.P., H.J. Iuzzolino, and J.S. Sandha, 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Comment. Page E-6: "Line 27 seems to contradict Page E-7 line 16. Can anoxic corrosion occur in the absence of <u>condensed</u> H_2O?"

Response. See Rechard, R.P., H.J. Iuzzolino, and J.S. Sandha, 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Comment. Page E-4: "Line 3 seems to contradict Page E-8 line 14. Is there 8.02 kg of cellulosics per drum or 6.90 kg?"

Response. See Rechard, R.P., H.J. Iuzzolino, and J.S. Sandha, 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Comment. Page E-10: "If the bulk density is 60% of the particle density, isn't the total volume of $CuSO_4$ required equal to $V = M/(p \cdot 0.6)$ or $V=(87800kh)/(3600 \cdot 0.6)=406$ m^3 (instead of $244m^3$)?"

Response. See Rechard, R.P., H.J. Iuzzolino, and J.S. Sandha, 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Response to Comments from EPA Office of Radiation Programs

on SAND88-1452

Draft Forecast of the Final Report
for the Comparison to 40 CFR Part 191, Subpart B
for the Waste Isolation Pilot Plant

and SAND89-2027

Performance Assessment Methodology Demonstration:
Methodology Development for Evaluating Compliance
with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant

GENERAL COMMENTS

SAND88-1452 has been updated. The new version is SAND90-2347, *Preliminary Comparison with 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant, December 1990*, to be followed in 1991 and 1992 with similar updates. The final report will be prepared in late 1993 and published in 1994 after extensive review.

SAND89-2027 will not be updated. SAND90-2347 supersedes it.

Comments Specific to SAND88-1452

Comment. "A section should be added on groundwater protection requirements to evaluate the quality of the groundwater found at WIPP and compare and classify groundwater in accordance with the groundwater protection requirements of the standard."

Response. A new chapter has been added for the groundwater protection requirements (§ 191.16). The 1985 Standard protected "special sources of groundwater," defined as Class I groundwater that simultaneously meets three specific criteria. Two of the three criteria require a population of thousands of persons to have been supplied drinking water from a special source of groundwater at the time the WIPP location was selected. Neither the population nor the drinking water supply exists at the WIPP; therefore, § 191.16 is not relevant to the WIPP. Discussing the third criterion, the classification of groundwater within 10 km of the waste panels, will not change this conclusion. The absence of Class I groundwater is discussed.

Comment. "The controlled area is described to be not less than the proposed land withdrawal boundary and not greater than the 40 CFR 191 limits. It should be made clear that the control [sic] area boundaries are to be identified by passive institutional controls. The EPA standard identifies the controlled area as, among other things, 'A surface location to be identified by passive institutional controls'."

Response. The statement (SAND88-1452, page VI-2, line 3), that "The Project will implement passive institutional controls over the entire controlled area, including markers, records, and federal ownership," is clarified as requested.

Comment. "On page II-5, the statement is made that EPA's use of the word 'incompatibility' is interpreted to mean that human intruders will plug and abandon boreholes. While 'incompatibility' does mean that human intruders will abandon the drilling, it does not mean that the holes will necessarily be plugged. The language in Appendix B of the 1985 issuance 40 CFR 191 Part B states 'Furthermore, the Agency assumes that the consequence of such inadvertent drilling need not be more severe than ... (2) 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."

Response. The Agency's assumption in the guidance is recognized as the most pessimistic conditions that would be reasonable in the absence of similar assumptions developed by the DOE. The WIPP performance assessment is assembling a data base on exploratory drilling in the Delaware Basin. The data base will be supplemented by expert judgment on the likelihood that an inadvertently intruding borehole will be plugged before it is abandoned. Probability density functions for borehole plugging will not be available for the 1990 update.

Comment. "For the human intrusion scenario, DOE should include information from studies they are performing for any conclusions they reach concerning borehole rates and plugging. As the 'Methodology Development' document points out, the standard gives no guidance for choosing the time borehole intrusion is assumed to first occur. Factors to be considered in determining drilling rates include past drilling history in the area, the likelihood of valuable resources being located under the site, and the passive institutional controls used to identify the controlled area. DOE, as the implementing agency, must determine and justify the degree that inadvertent, intermittent human intrusion will be reduced by passive institutional controls. Passive institutional controls may significantly reduce the drilling rate. The degree of that reduction and how it was derived and justified will be very important. An attempt should be made as early as possible to arrive at a consensus in these areas."

Response. Probability density functions derived from expert judgment on potential inadvertent intrusion by drilling over the 10,000 years of regulatory interest, including the factors outlined by EPA in this comment, will be available for the 1991 update. Passive institutional controls will be designed to reduce the drilling rate to the extent considered feasible by experts. The conclusions elicited from the expert panels currently convened to consider future societies and estimate the effectiveness of passive markers should be available for DOE and EPA review in 1991.

Comment. "While final probabilities have not been assigned yet for WIPP scenarios, insure that these probability assignments are explained. The reasoning behind the dismissal of scenarios will require more background information and explanation than presented in this document since low probabilities are determined 'subjectively.' This discussion should include what sources and expert opinion were sought to arrive at decisions. Although this work and the dismissal of these scenarios are only preliminary, it is important to work toward a consensus in the scientific community for probability values. The document also requires more information on how and where 'expert prevalent judgement' is to be gathered, analyzed, and decisions made."

Response. More background information from the literature is provided to explain why certain events and processes were screened out. A description of the process for eliciting expert judgement on human intrusion is included in the 1990 update.

Comment. "In discussing the EPA standard, this document quotes the standard's preamble language, 'If -- after substantial experience with these analyses is acquired -- disposal systems that clearly provide good isolation cannot reasonably be shown to comply with the containment requirements, the EPA would consider whether modifications to Subpart B were appropriate.' We would like to point out that work performed thus far at WIPP and our ongoing analysis indicate that the containment limits of the 1985 standard can be met. The 'Methodology Development' document shows that WIPP is capable of meeting the standard by an order of magnitude with engineered modifications. This preliminary conservative assessment shows the reference design WIPP room parameters and waste form can be a weakness in case of an inadvertent intrusion. A serious evaluation of modifications in the waste form or engineered modifications should be considered before changes in the containment limits would be appropriate. We feel the 'Methodology Development' analysis indicates the appropriateness of a probability-based standard that investigates the probability and consequence of various disruptive events (including human intrusion)."

Response. No such conclusions can be drawn from the demonstration analyses; they were clearly identified as incomplete and inadequate for decision-making. We agree that the appropriateness of a probability-based standard is substantiated by the analyses to date; however, these analyses have also shown the impracticality of emphasizing human intrusion in the uncertainty analyses. The analyses have shown that human intrusion totally dominates the results to the extent that the excellent geohydrology of the host rock becomes almost irrelevant for the WIPP. We believe that a serious evaluation of the regulatory impacts of the Standard on management and disposal of defense wastes should be performed by the EPA before conclusions such as "weakness of the reference design" are reached. Such a regulatory impact analysis could conceivably conclude that (1) the WIPP disposal system clearly provides good isolation from all likely events and processes except human intrusion, but "cannot reasonably be shown to comply with the Containment Requirements" if conservative scenarios for human intrusion are assumed, and (2) the EPA should consider whether modifications to Subpart B are appropriate. The regulatory impact analysis should examine the relative costs in both dollars and human exposure of modifying the waste form to maintain the degree of conservatism EPA chose for the Standard. The EPA stated in supplementary information provided with the Standard in Federal Register Vol. 50, No. 182 (the Standard's preamble language) that no regulatory impact analysis was performed for defense waste repositories.

Comment. "Long term effects of the disturbed rock zone (DRZ), if any, are not included in the physical processes simulated in the consequence modeling. It is not clear what the 'expected' conditions are regarding the existence of the DRZ in the surrounding salt for the undisturbed performance. The existence of the DRZ should be accounted for in modeling room closure from salt creep."

Response. The existence of the DRZ is accounted for in the modeling of brine and gas flow for the 1990 update.

Comment. "The objective of model calibration is to have equivalent travel times and results for the various models used. The groundwater travel times and ranges of those times used in these various conceptual models for the Culebra should be included in this document."

Response. Equivalency of travel times among models is the objective for NEFTRAN calibrations only. Groundwater travel times and ranges of those times for the performance-assessment conceptual models are reported in the documents describing steady-state and transient calibration of the SWIFT groundwater model using both pre-excavation data and various pumping and convergent tracer tests conducted between 1981 and 1989.

Comments Specific to SAND89-2027

This document will not be updated; therefore, all responses are from the perspective of SAND90-2347, the *Preliminary Comparison* for 1990.

Comment. "The physical mechanisms taking place in the repository should be the driving force for model development. Concentration on developing numerical models to fit experimental data and conceptual models without an understanding of these mechanisms should be avoided. We agree with the use of more than one conceptual model to describe the physical repository system and to account for the large uncertainties involved with predicting the performance of the repository over long periods of time. The level of confidence associated with each conceptual model used in this analysis should be included in updates of this document."

Response. The physical (and chemical, biological, etc.) mechanisms taking place in the repository are the driving forces for model development. These mechanisms cannot be understood without experimental data and conceptual models. The level of confidence associated with each conceptual model used in the performance assessment will be included as methods for assessing confidence are developed.

Comment. "The calculated CCDF is sensitive to the estimates and distribution of radionuclide solubility and other parameters. This shows the need for quality data on parameter endpoints and distribution selection. Where quality data does not exist, theoretical understanding, subjective expert judgement, and external review will be required. Although this is a demonstration, and not meant to show actual compliance, areas where prevalent expert judgement are used should be specifically identified and discussed in documents used to show compliance."

Response. The source or basis for distributions of parameters will be specifically identified. See Rechard, R. P., H. J. Iuzzolino, and J.S. Sandha. 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Comment. "While no release of radionuclides is projected during 1,000 years for undisturbed performance, this should be reevaluated when more gas generation data is received."

Response. Effects of gas generation will be included and undisturbed performance will be reevaluated as appropriate when data and models are available.

Comment. "The controlled area is described to be not less than the proposed land withdrawal boundary and not greater than the 40 CFR 191 limits. It should be made clear that the control [sic] area boundaries are to be identified by passive institutional controls. The EPA standard identifies the controlled area as, among other things, 'A surface location to be identified by passive institutional controls'."

Response. The statement (SAND88-1452, page VI-2, line 3), that "the Project will implement passive institutional controls over the entire controlled area, including markers, records, and federal ownership," is clarified as requested.

Comment. "For the human intrusion scenario, DOE should include information from studies they are performing for any conclusions they reach concerning borehole rates and plugging. As the 'Methodology Development' document points out, the standard gives no guidance for choosing the time borehole intrusion is assumed to first occur. Factors to be considered in determining drilling rates include past drilling history in the area, the likelihood of valuable resources being located under the site, and the passive institutional controls used to identify the controlled area. DOE, as the implementing agency, must determine and justify the degree that inadvertent, intermittent human intrusion will be reduced by passive institutional controls. Passive institutional controls may significantly reduce the drilling rate. The degree of that reduction and how it was derived and justified will be very important. An attempt should be made as early as possible to arrive at a consensus in these areas."

Response. Probability density functions derived from expert judgment on potential inadvertent intrusion by drilling over the 10,000 years of regulatory interest, including the factors outlined by EPA in this comment, will be available for the 1991 update. Passive institutional controls will be designed to reduce the drilling rate to the extent considered feasible by experts. The conclusions elicited from the expert panels currently convened to consider future societies and estimate the effectiveness of passive markers should be available for DOE and EPA review in 1991.

Comment. "The Compliance Assessment Methodology Controller (CAMCON) system automatically translates output data from one computer code to the input format of another. It should assist in avoiding operator errors and improve certain aspects of quality assurance. However, we do have concerns on the implementation of this type of program and the need for ensuring that subjective judgements the analyst may make are documented to avoid misapplication."

Response. More detail will be provided in CAMCON documentation on subjective judgments made by the analysts.

Comment. "The results illustrated in this methodology document indicate a need to aggressively pursue reduction of the uncertainties and conservatism used in this analysis. Although this performance assessment is for demonstration purposes only, its results point out concerns with disposing untreated waste at WIPP. In future analyses, conceptual models from SUTRA and the use of engineered modifications should be incorporated in the document, including the associated levels of confidence for those models. As the Test Phase of the WIPP repository yields more information, this demonstration should include those conceptual models as well."

Response. The results of the demonstration also point out the need for EPA to perform a regulatory impact analysis of the Standard for application to disposal of transuranic radioactive waste. Future performance analyses will incorporate appropriate conceptual models. Engineered modifications will be incorporated as DOE identifies what, if any, modifications are desirable. We caution EPA that conclusions such as "concerns with disposing untreated waste at WIPP" cannot be reliably drawn from incomplete, overly conservative calculations.

Comment. "The document states that extremely conservative predictions are being mimicked by NEFTRAN in the Culebra. Hydrological studies of this aquifer system are nearly complete, and more realistic predictions appear to be in order. This is especially true for assumptions of minimal retardation values and fracture flow in the Culebra."

Response. Numerical models are available now for making somewhat more realistic predictions. These are discussed and illustrated in the 1990 update.

Comment. "In considering the climate changes that are expected to occur over the next 10,000 years, climatic changes greater than two standard deviations from the mean of the distribution are considered extreme. The document asks if this criterion satisfies the intent of the standard for unlikely processes. This criterion applies to the undisturbed performance only. In evaluating climatic change for Section 191.13, the intent of the standard is to evaluate the probabilities of various magnitudes of climatic change based on historical reference and future climatic predictions taking into account variables such as the greenhouse effect if appropriate."

Response. Climatic change has been examined on a global scale for glaciation cycles. Human-induced climatological changes are beyond the intent of the Standard; they also take place on a much narrower time scale than global glaciation cycles and are unlikely to be as significant. Our approach for the 1990 preliminary assessment is to assume that change in average precipitation to a glacial maximum has a probability of 1.0 and bounds all other changes; thus climatic change is certain and must be included in all scenario analyses.

GLOSSARY

absorption - The entrance of surface water into the lithosphere by any method.

accessible environment - The accessible environment means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area *(40 CFR 191.12[k])*.

actinide - Any element in the actinium series of elements of increasing atomic number, beginning with actinium (89) and ending with lawrencium (103).

activation product - An isotope created from another isotope subjected to radiation.

adsorption - Adherence of gas molecules, or of ions or molecules in solution, to the surface of solids with which they are in contact.

advection - The process of transport of an aqueous property by mass motion.

algorithm - A procedure for solving a mathematical problem in a finite number of steps that frequently involves repetition of an operation.

anhydrite - A mineral consisting of anhydrous calcium sulfate ($CaSO_4$). It is gypsum without water, and is denser, harder, and less soluble.

anisotropic - Pertaining to any material property, such as hydraulic conductivity, that varies with direction.

anoxic - Without free oxygen.

anticline - A fold of rocks, generally convex upward, whose core contains stratigraphically older rocks.

aperture - The open space along a fracture in rock.

aquifer - A body of rock that is sufficiently permeable to conduct groundwater and to yield significant quantities of groundwater to wells and springs.

aquitard - A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer.

argillaceous - Containing clay-sized particles or clay minerals.

backfill - Material placed around the waste containers, filling the open space in the room.

backpressure - Pressure caused by a force operating in a direction opposite to that being considered, such as that of a pore fluid pressure on matrix.

barrier - "Barrier means any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides." *(40 CFR 191.12[d])*

basin - A depression in the Earth's crust in which sediments have accumulated.

bed rock - A solid, in-place rock that is exposed at the surface or underlies soil or other unconsolidated surficial deposits.

Bell Canyon Formation - A sequence of rock strata that form the topmost formation of the Delaware Mountain Group (Early Permian).

benchmark - To compare predictions made with one code with those obtained with other codes or with analytical solutions. Benchmarking is a part of verification.

bentonite - A commercial term applied to clay materials containing montmorillonite (smectite) as the essential mineral.

biosphere - The life zone of the earth, including the lower part of the atmosphere, the hydrosphere, soil, and the lithosphere to a depth of about 2 km (1 mi).

biotransport - Movement of radionuclides over biological pathways, such as through the food chain.

borehole - (1) A manmade hole in the wall, floor, or ceiling of a subsurface room used for verifying geology, making observations, or emplacing canisters of remote-handled transuranic (RH-TRU) waste. (2) A hole drilled from the surface for purposes of geologic or hydrologic testing, or to explore for resources; sometimes referred to as a drillhole.

breccia - A rock consisting of very angular, coarse fragments held together by a mineral cement or a fine-grained matrix (as sand or clay).

breccia pipe - A vertically cylindrical feature filled with collapse debris. It is formed when relatively fresh water from a deep-seated aquifer moves upward through fractures, dissolving evaporites and causing collapse of the surrounding rock material.

brine aquifer - The Rustler-Salado residuum, a zone of residual material, left after dissolution of the original salt at the interface of the Rustler and Salado Formations, that is highly permeable and contains much brine.

brine inclusion - A small cavity in a rock mass (salt) containing brine; also, the brine included in such an opening. Some gas is often present.

brine occurrence - Hydraulically isolated, stagnant pocket of pressurized fluid in the Castile Formation; also referred to as "brine pocket" or "brine reservoir."

brine pocket - See brine occurrence.

brine reservoir - See brine occurrence.

calibrate - To fit and/or tune computational models to simulate observed data.

caliche - A calcareous material commonly found in layers on the surface of or within stony soils of arid or semi-arid regions. It occurs as gravels, sands, silts, and clays cemented together by calcium carbonate (lime) or as crusts at the surface of the soil.

canister - A container, usually cylindrical, for remotely handled waste, spent fuel, or high-level waste; affords physical containment but not radiation shielding. Waste remains in its canister during and after burial.

capacitance - In hydrology, the combined compressibility of the solid porous matrix and the fluid within the pores.

Capitan Reef - A fossilized limestone reef of the Permian Period that surrounds most of the Delaware Basin.

cask - A shipping container that is radiation shielded.

Castile Formation - A stratigraphic unit of evaporite rocks (interbedded halite and anhydrite) of the Permian Period that immediately underlies the Salado Formation (in which the WIPP disposal level is being built).

Cenozoic - An era of geologic time from the beginning of the Tertiary Period (about 66 million years ago) to the present.

chlorite - Any of a group of magnesium-, aluminum-, and iron-bearing hydrous silicate minerals. Their layered, sheet-like structure is similar to that of clays and micas.

clastic - Rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals.

claystone - An indurated clay having the texture and composition of shale but lacking the fine lamination and fissility.

cokriging - Geostatistical technique for estimating two (or more) variables that are correlated for field measurements at different locations.

compaction - Mechanical process by which the pore space in the waste is reduced prior to waste emplacement.

complementary cumulative distribution function (CCDF) - One minus the cumulative distribution function.

compliance evaluation or assessment - The process of assessing the regulatory compliance of a mined geologic waste repository.

compressibility - A measure of the ability of a substance to be reduced in volume by application of pressure; quantitatively, the reciprocal of the bulk modulus.

computational model - The computer model plus the appropriate values for the parameters.

computer model - The appropriately coded analytical, quasi-analytical, or numerical solution technique used to solve a mathematical model.

conceptual model - The set of hypotheses and data that postulate the description and behavior of the disposal system (e.g., structural geometry, material properties, and all significant physical processes that affect behavior). For WIPP, the data pertinent for a conceptual model are stored in the secondary data base. Several secondary data bases exist because each scenario may have a slightly different conceptual model.

conductivity - A shortened form of hydraulic conductivity.

confined groundwater - Groundwater under pressure significantly greater than atmospheric pressure. Its upper surface is the bottom of an impermeable bed or a bed of distinctly lower permeability than the material in which the water occurs.

confirm - To use full-scale in situ experiments to corroborate portions of parameter ranges or distributions established by laboratory or small-scale tests.

conformable - Strata or stratification characterized by an unbroken sequence in which the layers are formed one above the other by regular, uninterrupted deposition.

consolidate - To cause loosely aggregated, soft, or liquid earth materials to become firm and coherent rock.

consolidation - Process by which backfill and waste mass loses pore space in response to the increasing weight of overlying material.

Consultation and Cooperation (C&C) Agreement - An agreement that affirms the intent of the Secretary of Energy to consult and cooperate with the State of New Mexico with respect to State public health and safety concerns. It is an appendix to a July 1981 agreement (the Stipulated Agreement) made with the State and approved by the District court when that court stayed the proceedings of a lawsuit against the DOE by the State. The C&C agreement identifies a number of "key events" and "milestones" in the construction and operation of the WIPP that must be reviewed by the State before they are started. The C&C agreement has been updated and extended as recently as March 1988.

controlled area - The controlled area means "(1) a surface location, to be identified by passive institutional controls, that encompasses no more that 100 km and extends horizontally no more than 5 km in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location." *(40 CFR 191.12[g])*

creep - A usually very slow deformation of solid rock resulting from constant stress; refers to the gradual flow of salt under high compressive loading.

creep closure - Closure of underground openings, especially openings in salt, by plastic flow of the surrounding rock under pressure.

Cretaceous - Last period of the Mesozoic Era, about 66 to 144 million years ago.

criticality - The state of a mass of fissionable material when it is sustaining a chain reaction.

Culebra Dolomite Member - The lower of two layers of dolomite within the Rustler Formation that are locally water bearing.

cumulative distribution function - The sum (integral) of the probability density of frequency values that are less than or equal to a specified value.

curie - Ci; a unit of radioactivity equal to the number of disintegrations per second of 1 pure gram of radium-226 (1 Ci = 3.7×10^{10} disintegrations per second).

cuttings - Rock chips cut by a bit in the process of drilling a borehole or well.

Darcian - Pertaining to a formula derived by Darcy for the flow of fluids, with the assumption that the flow is laminar and that inertia can be neglected.

darcy - An English standard unit of permeability, defined by a medium for which a flow of 1 cm^3/s is obtained through a section of 1 cm^2, for a fluid viscosity of 1 cP and a pressure gradient of 1 atm/cm. One darcy is equal to 9.87×10^{-13} m^2.

decommissioning - Actions taken upon abandonment of the repository to reduce potential environmental, health, and safety impacts, including repository sealing as well as activities to stabilize, reduce, or remove radioactive materials or to demolish surface structures.

decontamination - The removal of radioactive contamination from facilities, equipment, or soils by washing, heating, chemical or electrochemical treating, mechanical cleaning, or other techniques.

Delaware Basin - The part of the Permian Basin in southeastern New Mexico and adjacent parts of Texas where a sea deposited large thicknesses of evaporites between approximately 260 and 250 million years ago. It is partially surrounded by the Capitan Reef.

Delaware Mountain Group - A set of three formations of the Permian Period that underlie the Castile Formation at the Los Medaños site.

depositional - The accumulation of loose rock material by an natural agent.

desaturate - To remove liquid from a material until it is no longer saturated.

deterministic - An exact mathematical relationship between the dependent and independent variables in a system.

Dewey Lake Red Beds - A formation of the Permian Period that overlies the Rustler Formation and is composed of reddish-brown marine mudstones and siltstones interbedded with fine-grained sandstone.

diapirism - The process of piercing or rupturing sedimentary rocks by mobile core material due to geostatic load, producing domed or uplifted rocks.

diastrophism - All movement of the crust produced by tectonic processes, including the formation of ocean basins, continents, plateaus, and mountain ranges.

diffusive - Characterized by the transfer of chemical components from a region of higher to lower concentration.

disposal - "Disposal means permanent isolation of spent nuclear fuel or radioactive waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such fuel or waste. For example, disposal of waste in a mined geologic repository occurs when all of the shafts to the repository are backfilled and sealed." *(40 CFR 191.02[1])*

disposal system - Any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal *(40 CFR 191.12(a))*. The natural barriers extend to the accessible environment. The WIPP disposal system comprises the underground repository, shafts, and controlled area.

disturbed rock zone - That portion of the controlled area the physical or chemical properties of which have changed as a result of underground construction such that the resultant change of properties may have a significant effect on the performance of the geologic repository.

Dockum Group - A geologic sedimentary sequence of the Triassic Period that overlies the Dewey Lake Red Beds over part of the Los Medaños area.

dolomite - A carbonate sedimentary rock consisting of more than 50% of the mineral dolomite $[CaM_g(CO_3)_2]$.

dose - A general term indicating the amount of energy absorbed per unit mass from incident radiation.

dose equivalent - The product of absorbed dose and modifying factors that take into account the biological effect of the absorbed dose. While dose includes only physical factors, dose equivalent includes both physical and biological factors and provides a radiation-protection scale applicable to all types of radiation. Units are rem for individual and person-rem for a population group.

dosimetry - The measurement of radiation doses.

drawdown - The lowering of water level in a well as a result of fluid withdrawal.

drift - A horizontal passageway in a mine.

dynamical - A family of solutions to an ordinary differential equation.

emplacement - At WIPP, the placing of radioactive wastes within the waste rooms.

Eocene - An epoch of the early Tertiary Period (or Paleogene Period), subsequent to the Paleocene Epoch and preceding the Oligocene Epoch (about 37 to 58 million years ago).

eolian - Pertaining to the wind; especially said of sedimentary deposits and features formed by wind action.

equipotential - Points with the same hydraulic head elevations.

equivalent grams plutonium-239 - Fissionable content of radioactive waste converted to an equivalent number of grams of plutonium-239.

Eulerian - Pertaining to a mathematical representation of fluid flow in which the behavior and properties of the fluid are described at fixed points within the coordinate system.

evaporite - A sedimentary rock composed primarily of minerals produced by precipitation from a solution that has become concentrated by the evaporation of a solvent, especially salts deposited from a restricted or enclosed body of seawater or from the water of a salt lake. In addition to halite (NaCl), these salts include potassium, calcium, and magnesium chlorides and sulfates.

event - A phenonenon that occurs instantaneously or within a short time interval relative to the time frame of interest.

exploratory drilling - Drilling to an unexplored depth or in territory having unproven resources.

facies - An areally restricted part of a rock body that differs in mineralogic composition, grain size, or fossil content from nearby beds deposited at the same time and that broadly corresponds to a certain environment or mode of deposition.

facility - The surface structures of the repository.

finding - A conclusion that is reached after an evaluation.

fissile - Capable of being split along closely spaced planes.

fission product - Any radioactive or stable nuclide resulting from fission, including both primary fission fragments and their radioactive decay products.

flowpath - The path traveled by a neutrally buoyant particle released into a groundwater-flow field.

fluvial - Of or pertaining to a river or rivers.

foraminifera - Any of various fossil and living species of marine and freshwater protozoans, class Foraminifera, characterized by calcite, silica, aragonite, or agglutinated shells.

fossiliferous - Containing remains, traces, or imprints of plants or animals that have been preserved in the Earth's crust since some past geologic or prehistoric time.

geochemistry - The study of the distribution and amounts of the chemical elements in minerals, ores, rocks, soils, water, and the atmosphere.

geohydrology - The study of the hydrologic or flow characteristics of subsurface waters.

geology - The study of the Earth, the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms since its origin.

geomorphology - The study of the classification, description, nature, origin, and development of present landforms and their relationships to underlying structure, and of the history of geologic changes as recorded by these surface features.

geophysics - The study of the Earth by quantitative physical methods such as electric, gravity, magnetic, seismic, and thermal techniques.

geosphere - The solid portion of the Earth as compared to the atmosphere and the hydrosphere.

getter - A substance that sorbs gases.

glaciation - The formation, movement, and recession of glaciers or ice sheets. Used narrowly, the term can refer only to the growth of ice sheets.

glauberite - A brittle, light-colored, monoclinic mineral: $Na_2Ca(SO_4)_2$. It has a vitreous luster and saline taste and occurs in saline residues.

grout - A cement slurry of high water content.

Guadalupian - A North American geologic series, above the Leonardian Series and below the Ochoan Series, that corresponds to portions of the Early and Late Permian Period (about 253 to 263 million years ago).

gypsiferous - Containing gypsum, hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$), a mineral frequently associated with halite and anhydrite in evaporites.

halite - A dominant mineral in evaporites; salt, NaCl.

halogenated - Atoms from the halogen family of elements combined with other atoms such as carbon.

Holocene - A geologic epoch of the Quaternary Period, subsequent to the Pleistocene Epoch (about 10,000 years ago) and continuing to the present.

horizon - In geology, an interface indicative of a particular position in a stratigraphic sequence. An underground level; for instance, the waste-emplacement horizon at the WIPP is the level about 650 m (2,150 ft) deep in the Salado Formation where openings are mined for waste disposal.

host rock - The geologic medium in which radioactive waste is emplaced.

hot cell - A heavily shielded compartment in which highly radioactive material can be handled, generally by remote control.

hydraulic - Pertaining to a fluid in motion.

hydraulic conductivity - The measure of the rate of flow of water through a cross-sectional area under a unit hydraulic gradient.

hydraulic gradient - A quantity defined in the study of ground-water hydraulics that describes the rate of change of total hydraulic head per unit distance of flow in a given direction.

hydraulic head - The elevation to which water rises at a given point as a result of reservoir pressure.

hydrochemical - The diagnostic chemical character of ground water occurring in hydrologic systems.

hydrogeology - The study of subsurface waters and of related geologic aspects of surface waters.

hydrologic properties - Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.

hydrology - The study of global water, its properties, circulation, and distribution.

hydropad - A complex of hydro-wells closely spaced for testing on hydrostratigraphic units.

hydrostratigraphic - Pertaining to a body of rock having considerable lateral extent and composing a geologic framework for a reasonably distinct hydrologic system.

in situ - In the natural or original position; used to distinguish in-place experiments, rock properties, and so on, from those in the laboratory.

interbeds - Sedimentary beds that lie between or alternate with other beds having different characteristics.

interfinger - The disappearance of sedimentary bodies into laterally adjacent masses by splitting into many thin layers, each terminating independently.

interpolators - Computer programs used to estimate an intermediate value of one (dependent) variable which is a function of a second variable.

intertonguing - The lateral intergradation of different rock types through a vertical succession of thin, interlocking or overlapping, wedge-shaped layers.

intracrystalline - Pertaining to something within a mineral crystal.

ionic strength - A measure of the average electrostatic interaction among ions in a solution; a function of both concentration and valence of the solutes.

isolation - Refers to inhibiting the transport of radioactive material so that the amounts and concentrations of this material entering the accessible environment will be kept within prescribed limits.

isopach - A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units.

isotherm - A line on a map connecting points of equal temperature.

isotope - A species of atom characterized by the number of protons and the number of neutrons in its nucleus. In most instances, an element can exist as any of several isotopes, differing in the number of neutrons, but not the number of protons, in their nuclei. Isotopes can be either stable isotopes or radioactive isotopes (also called radioisotopes or radionuclides).

isotropic - Independent material properties that are constant regardless of direction of movement.

iterative - A computational procedure in which replication of a cycle of operations produces results which approximate the desired result more and more closely.

jointing - The condition or presence of parallel fractures or partings in a rock, without displacement.

Jurassic - The second period of the Mesozoic Era, subsequent to the Triassic Period and preceding the Cretaceous Period (about 144 to 208 million years ago).

karst - A topography formed from solution of limestone, dolomite, or gypsum; characterized by sinkholes, caves, and underground drainage.

kriging - Geostatistical method for optimizing the estimation of a magnitude (e.g., hydrogeological parameters), which is distributed in space and is measured at a network of points.

lacustrine - Pertaining to a lake or lakes.

Lagrangian - Pertaining to a mathematical representation of fluid flow in which the behavior and properties of the fluid are described for elements that move with flow.

Laguna Grande de la Sal - The largest lake in the Los Medaños area, located southwest of the WIPP.

langbeinite - A colorless to reddish mineral [$K_2Mg_2(SO_4)_3$] used as a source of potassium in fertilizers and formed as a saline residue from evaporation.

Latin hypercube sampling - A Monte Carlo sampling technique that divides the distribution into intervals of equal probability and samples from each interval.

lenticular - Having the cross-sectional shape of a lens, esp. of a double-convex lens. The term may be applied to a body of rock or a sedimentary structure.

Leonardian - A North American geologic series, above the Wolfcampian Series and below the Guadalupian Series, that corresponds to the Early Permian Period (about 263 to 268 million years ago).

ligands - Ions bound to a central atom in a compound.

lithologic - The descriptive characteristics of rock composition.

lithosphere - The solid portion of the earth, including any groundwater contained within it, as opposed to the atmosphere and the hydrosphere.

lithostatic pressure - Subsurface pressure caused by the weight of overlying rock or soil, about 14.9 MPa at the WIPP repository level.

Livingston Ridge - Topographic feature marking the eastern boundary of Nash Draw.

Los Medaños - Literally "the dunes." The area in which the WIPP is located.

Malaga Bend - Prominent bend in the Pecos River, southwest of the WIPP.

management - "Management means any activity, operation, or process (except for transportation) conducted to prepare spent nuclear fuel or radioactive waste for storage or disposal, or the activities associated with placing such fuel or waste in a disposal system." *(40 CFR 191.02[m])*

material - Substance (e.g., rock type) with physical properties that can be expressed quantitatively, from which a numerical model can be constructed.

material property - Characteristic of the material that remains constant throughout the numerical mesh.

mathematical model - The mathematical representation of a conceptual model (e.g., the coupled algebraic, differential, or integral equations with proper boundary conditions that approximate the physical processess in a specified domain of the conceptual model).

Mescalero caliche - Informal name for mid-Pleistocene (approximately 510,000 years ago) caliche occurring in southeastern New Mexico.

mesh - A computational grid generated by a computer program.

Mesozoic - The era of geologic time from about 66 to 245 million years ago.

microcrystalline - Crystals too small to see with the naked eye.

microdarcy (μd) - A unit of measurement of fluid permeability, equivalent to 10^{-6} darcy or 9.87×10^{-19} m^2.

microfracturing - The formation of fractures that cannot be detected with the unaided eye.

millidarcy (md) - Unit of measurement of fluid permeability, equivalent to 10^{-3} darcy or 9.87×10^{-16} m^2.

Miocene - An epoch of the early Tertiary Period, subsequent to the Oligocene Epoch and preceding the Pliocene Epoch (about 5 to 24 million years ago).

modeler - One who formulates a working hypothesis or precise simulation, by means of description, statistical data, or analogy, of a phenomenon or process that cannot be observed directly.

modular - Constructed with standardized units or dimensions for flexibility and variety in use.

module - A standardized unit or packaged functional computer program assembly.

molal - Concentration of a solution expressed in moles of solute per 1000 grams of solvent.

Monte Carlo sampling - A random sampling technique using computer simulation to obtain approximate solutions to mathematical or physical problems, especially in terms of a range of values each of which has a calculated probability of being the solution.

mud - In drilling, a carefully formulated heavy suspension, usually in water but sometimes in oil, used in drilling to lubricate and cool the drill bit, carry cuttings up from the bottom, and maintain a hydrostatic pressure in the borehole to offset pressures of fluids in the formation.

mudstone - A blocky or massive, fine-grained sedimentary rock in which the proportion of clay and silt are approximately equal.

multipad - See hydropad.

nanodarcy (nd) - A unit of measurement of fluid permeability, equivalent to 10^{-9} darcy or 9.87×10^{-22} m^2.

Nash Draw - A shallow, 5-mile-wide valley located to the west of the WIPP and open to the southwest.

neoprene - A synthetic rubber made by the polymerization of chloroprene.

Newtonian - Pertaining to a substance in which the rate of shear strain is directly proportional to the shear stress.

noncombustibles - Materials that will not burn.

nuclide - A species of atom characterized by the construction of its nucleus.

Ochoan - A North American geologic series, above the Guadalupian Series and below the Lower Triassic Series, corresponding to the Late Permian Period (about 248 to 253 million years ago).

Ogallala Formation - A sequence of late Tertiary Period (Miocene and Pliocene Epochs) sandstones and conglomerates widely distributed in the American Great Plains.

Oligocene - An epoch of the early Tertiary Period, subsequent to the Eocene Epoch and preceding the Miocene Epoch (about 24 to 38 million years ago).

Ordovician - The second earliest period of the Paleozoic Era, subsequent to the Cambrian Period and preceding the Silurian Period (about 408 to 505 million years ago).

organics - Compounds containing carbon.

ostracode - Any of various fossil and living species of marine and freshwater bivalve crustaceans, subclass Ostracoda.

overexcavation - Excavation of the disturbed rock zone prior to emplacement of a seal.

overpack (waste) - A container put around another container. In the WIPP, overpacks would be used on damaged or otherwise contaminated drums, boxes, and canisters that it would not be practical to decontaminate.

oxygen-18/oxygen-16 ratio - Comparison of the amount of oxygen-18 and oxygen-16 in a substance. Ratios in sea water reflect global volume of glacial ice.

oxyhydroxides - Compounds containing an oxide and a hydroxide group: e.g., goethite ($\alpha FeO \cdot OH$) and limonite ($FeO \cdot OH \cdot nH_2O$).

Paleocene - An epoch of the early Tertiary Period, subsequent to the Late Cretaceous Period and preceding the Eocene Epoch (about 58 to 66 million years ago).

paleoclimate - A climate of the geologic past.

panel - A group of several underground rooms bounded by two pillars and connected by drifts. Within the WIPP, a panel usually consists of seven rooms connected by 10-m-wide drifts at each end.

parameter - See variable.

particulate - Minute separate particles.

pascal (Pa) - Unit of pressure produced by a force of 1 newton applied over an area of 1 m^2. One pound per square inch is equal to 6.895×10^3 Pa.

passive institutional control - "Passive institutional control means (1) permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system." *(40 CFR 191.12[e])*

Pecos River - Major river in eastern New Mexico and western Texas.

Pennsylvanian - Second to the last Paleozoic period (about 286 to 320 million years ago).

perched groundwater - Unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone. Its water table is a perched water table. Perched groundwater is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

performance assessment - The process of assessing the compliance of a deep, geologic, waste repository with the containment requirements of *40 CFR 191*, Subpart B. Performance assessment is defined by Subpart B as "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." *(40 CFR 191.12(q))*

permeability - A measurement of the ability of a rock or soil to allow fluid to pass through it.

Permian - The last period of the Paleozoic Era, subsequent to the Pennsylvanian Period (about 245 to 286 million years ago).

Permian Basin - A region in the south-central United States, where during the Permian Period (245 to 286 million years ago), there were many shallow sub-basins in which vast beds of marine evaporites were deposited.

pillar - Rock left in place after mining to provide underground vertical support.

pintle - A cylindrical flanged device on the end of an RH-TRU waste canister used for grasping and lifting the canister.

planktonic - Pertaining to aquatic organisms that drift or weakly swim near the water surface.

playa - An intermittently dry, vegetation-free, flat area at the lowest part of an undrained desert basin, underlain by stratified clay, silt, or sand, and commonly by soluble salts.

Pleistocene - An epoch of the Quaternary Period, subsequent to the Pliocene Epoch of the Tertiary Period and preceding the Holocene Epoch (about 1.6 million years ago to 10,000 years ago); corresponds to the "Great Ice Age."

Pliocene - An epoch of the Tertiary Period, subsequent to the Miocene Epoch and preceding the Pleistocene Epoch (about 1.6 to 5 million years ago).

plutonium - A reactive metallic element, symbol Pu, atomic number 94, in the transuranium series of elements; used as a nuclear fuel, to produce radioactive nuclides for research, and as a fissile agent in nuclear weapons.

pluvial - Of a geologic episode, change, deposit, process, or feature resulting from the action or effects of rain.

polyethylene - Various partially crystalline lightweight thermo-plastics made from ethylene.

polyhalite - An evaporite mineral: $K_2MgCa_2(SO_4)_4.2H_2O$; a hard, poorly soluble mineral.

polypropylene - A plastic made from propylene.

polyvinyl - A plastic made from vinyl chloride.

porosity - The percentage of total rock volume occupied by voids.

post-depositional - Occurring after sediments have been laid down.

potash - Specifically K_2CO_3. Also loosely used for many potassium compounds, especially as used in agriculture or industry.

potential - A function or set of functions of position in space, from whose first derivatives a vector can be formed, such as that of a static field intensity.

potentiometric surface - An imaginary surface representing the total head of ground water and defined by the level to which water will rise in a well.

predictive - Estimates of future states of a system.

probabilistic - Using the probability of a given set of events from a family of outcomes.

process - A phenomenon that occurs over a significant portion of the time frame of interest.

Quahada Ridge - Topographic feature marking the western boundary of Nash Draw.

quality assurance - All those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Quaternary - The second period of the Cenozoic Era, subsequent to the Tertiary Period, starting about 1.6 million years ago and continuing to the present.

rad - A basic unit of absorbed dose defined as an energy absorption of 100 erg/g of a specified material from any ionizing radiation.

radioactive waste - Solid, liquid, or gaseous material of negligible economic value that contains radionuclides in excess of threshold quantities.

radioactivity - The emission of energetic particles and/or radiation during radioactive decay.

radiological - Nuclear radiation and radioactivity.

radiolysis - The damage to a material caused by radiation.

radiometric - Pertaining to the disintegration of radioactive elements.

radionuclide - A radioactive nuclide.

radionuclide retardation - The process or processes that cause the time required for a given radionuclide to move between two locations to be greater than the ground-water travel time, because of physical and chemical interactions between the radionuclide and the geohydrologic unit through which the radionuclide travels.

recharge - The processes involved in the addition of water to the ground-water zone of saturation.

reentrant - A prominent, generally angular indentation in a land form.

rem - Roentgen equivalent man - a special unit of dose equivalent which is the product of absorbed dose, a quality factor which rates the biological effectiveness of the radiation types producing the dose, and other modifying factors (usually equal to one). If the quality and modifying factors are units, 1 rem is equal to 1 rad.

repository - The portion of the WIPP repository/shaft system within the Salado Formation, including the access drifts, waste panels, and experimental areas, but excluding the shafts.

repository/shaft system - The WIPP underground workings, including the shafts, and all emplaced materials and the altered zones within the Salado Formation and overlying units resulting from construction of the underground workings.

retardation - The degree to which the rate of radionuclide migration is reduced below the velocity of fluid flow.

retardation factor - Fluid velocity divided by mean radionuclide velocity for any specific element.

retrieval - The act of intentionally removing radioactive waste before repository decommissioning from the underground location at which the waste had been previously emplaced for disposal.

risk - A representation of the potential of a system to cause harm, represented by combining the likelihood of undesirable occurrences and the negative effects associated with such occurrences. A precise representation of risk is a set $\mathbf{R} = \{(S_i, pS_i, cS_i), i = 1, \ldots, nS\}$ of ordered triples, where S_i is a set of similar occurrences, pS_i is the probability of S_i, cS_i is a vector of consequences associated with S_i, and nS is the number of sets.

room - An excavated cavity underground. Within the WIPP, a room is 10 m wide, 4 m high, and 91 m long.

Rustler Formation - A sequence of Late Permian age clastic and evaporite sedimentary rocks that contains two dolomite members and overlies the Salado Formation.

Salado Formation - A Permian age sequence of salt with minor amounts of clay and anhydrite. Host unit for the WIPP.

saturated - All the pores in a given volume of rock contain fluid.

scenario - A combination of naturally occurring or human-induced events and processes that represents realistic future changes to the repository, geologic, and geohydrologic systems that could effect the escape of radionuclides from the repository, and release to the accessible environment.

seal - An engineered barrier designed to isolate the waste panels or to impede groundwater flow in the shafts.

sealing - Formation of barriers within man-made penetrations (shafts, drill-holes, tunnels, drifts).

sedimentation - The action or process of forming or depositing rock particles in layers.

shaft - A man-made hole, either vertical or steeply inclined, that connects the surface with the underground workings of a mine.

significant source of groundwater - "Significant source of ground water means: (1) An aquifer that: (i) is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface; (iii) has a transmissivity greater than 200 gallons per day per foot, provided, that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than two gallons per day per square foot; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of this subpart." *(40 CFR 191.12[n])*

siltstone - A sedimentary rock composed of at least two-thirds silt-sized grains (1/256 to 1/16 mm); it tends to be flaggy, containing hard, durable, generally thin layers.

sinkhole - A hollow in a limestone region that communicates with a cavern or passage.

sludge - A muddy or slushy mass, deposit, or sediment.

smectite - A general term for clay minerals of the montmorillonite group that possess swelling properties and high cation-exchange capacities.

solute - The material dissolved in a solvent.

sorb - To take up and hold by either adsorption or absorption.

source term - The kinds and amounts of radionuclides that make up the source of a potential release of radioactivity. For the performance assessment, the source term is defined as the sum of the quantities of the important radionuclides in the WIPP inventory that will be mobilized for possible transport to the accessible environment, and the rates at which these radionuclides will be mobilized.

special source of groundwater - "Special source of ground water means those Class I ground waters identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984 that: (1) are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that DOE chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the *NWPA* and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population." *(40 CFR 191.12[o])*

Standard - 40 CFR Part 191, *Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule.*

stochastic process - Involving a random variable or random vector synonymous with random function or random process.

storativity - The volume of water released by an aquifer per unit surface area per unit drop in hydrologic head.

stratabound - A deposit confined to a single stratigraphic unit.

stratigraphy - The study of rock strata; concerned with the original succession and age relations of rock strata, their form, distribution, lithologic composition, fossil content, and geophysical and geochemical properties.

surfactant - A surface active substance.

sylvite - A white or colorless mineral (KCl), the principal ore mineral of potassium compounds, that occurs in beds as a saline residue from evaporation.

syncline - A fold having stratigraphically younger rock material in its center; it is usually concave upward.

Tamarisk Member - A sequence of anhydrite, claystone, and siltstone within the Late Permian Rustler Formation of southeastern New Mexico.

tectonic - The forces involved in, or the resulting structures and features of, movements of the Earth's crust.

topographic - The configuration of a land surface, including its relief and the position of its natural and man-made features.

tortuosity - Measurement of actual path of flow through a porous medium.

transiency - Ability to affect something or produce results beyond itself.

translator - A computer program that translates output from one program to input for another program. Also referred to as pre- and post-processors.

transmissivity - The rate at which water of the prevailing viscosity is transmitted through a unit width of the aquifer under a hydraulic gradient.

transuranic radioactive waste (TRU waste) - Waste that, without regard to source or form, is contaminated with more than 100 nCi of alpha-emitting transuranic isotopes with half-lives greater than 20 yr, per gram of waste, except for (1) HLW; (2) wastes that the DOE has determined, with the concurrence of the EPA Administrator, do not need the degree of isolation required by *40 CFR 191*; or (3) wastes that the NRC Commission has approved for disposal on a case-by-case basis in accordance with *10 CFR 61*. Heads of DOE field organizations can determine that other alpha-contaminated wastes, peculiar to a specific site, must be managed as TRU waste.

Triassic - The first period of the Mesozoic Era, subsequent to the Permian Period and preceding the Jurassic Period (about 208 to 245 million years ago).

unconfined - Not confined under pressure beneath relatively impermeable rocks.

unconformably - Not conformable, i.e., a break in deposition of sedimentary material.

unconsolidated - Material that is loosely arranged or whose particles are not cemented together.

undisturbed performance - "The predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." (*40 CFR 191.12(p)*)

uniform distribution - A pdf that is a horizontal line, i.e., the model for the time of occurrence of an event that is equally likely to occur at any time during an interval.

unsaturated - Refers to a rock or soil in which the pores are not completely full of water.

uranyl - Prefix for compounds containing uranium.

Uranium-234/Uranium-238 activity ratio - Comparison of the radioactivities of U-234 and U-238; the change in this ratio is directly related to the passage of time because the two isotopes have very different half-lives, allowing the calculation in years of the age of a substance.

validate - To establish confidence that the model (and the associated computer program) correctly simulates the appropriate physical and chemical phenomena. Validation is accomplished through either laboratory or in situ experiments, as appropriate.

validation - The process of assuring through sufficient testing (subjective) with real site data that a conceptual model and the corresponding mathematical and computer models correctly simulate a physical process sufficiently accurately (subjective).

variable - Any quantity supplied to a model or a computer program that implements a model; also referred to as a parameter.

verification - The process of assuring that a computer program (computational model) correctly performs the operation specified in a numerical model. Each computational model must be verified and the verification documented. Benchmarking is a verification method that compares the results produced by one computational model against results produced by other computational models that solve similar problems.

water table - In saturated rock, the surface of the water that is at atmospheric pressure.

WIPP land withdrawal- Sixteen contiguous sections proposed to be withdrawn from public access to be used for the disposal of TRU waste.

Wolfcampian - A North American geologic series, above the Virgilian Series and below the Leonardian Series, that corresponds to the Early Permian Period (about 268 to 286 million years ago).

NOMENCLATURE

Acronyms and Initialisms

AEC - Atomic Energy Commission

AKRIP - computer program used for kriging

AL - Albuquerque Operations Office

ALGEBRA - Computer program that algebraically manipulates data and plots meshes and curves.

ASCII - American Standard Code for Information Exchange

BLOT - A mesh-and-curve-plotting computer program.

BOAST II - A computational computer program that simulates three-phase flow (oil, water, and gas) in a three-dimensional, porous medium.

BRWM - Board on Radioactive Waste Management of the National Research Council

C2FINTRP - Computer program that interpolates boundary conditions from a coarse to fine mesh.

CAM - Compliance Assessment Methodology

CAMCON - Compliance Assessment Methodology CONtroller; controller (driver) for compliance evaluations developed for the WIPP.

CAMDAT - Compliance Assessment Methodology DATa base; computational data base developed for the WIPP.

CAM2TXT - Computer program for binary CAMDAT to ASCII conversion.

CAS - compliance assessment system

CCDF - complementary cumulative distribution function

CCDFCALC - computer program used to calculate a CCDF

CCDFPLT - Computer program that calculates and plots the complementary cumulative distribution function.

cdf - cumulative distribution function

CFR - Code of Federal Regulations

CH-TRU - Contact-Handled TRansUranic waste, packaged TRU waste whose external surface dose rate does not exceed 200 mrem per hour.

CUTTINGS - Computer program for evaluating the amount of material removed during drilling.

DOE - The U.S. Department Of Energy, established in 1978 as a successor to ERDA and the AEC.

DRZ - disturbed rock zone

DST - drill-stem test

E1 - An event used to develop scenarios: intrusion of a borehole through a disposal panel into a pressurized brine occurrence in the Castile Formation, or a simplified notation for a scenario in which event E1 occurs and other events do not ($\overline{TS}$, E1, $\overline{E2}$).

E2 - An event: intrusion of a borehole into a disposal panel, or a simplified notation for a scenario in which event E2 occurs and other events do not ($\overline{TS}$, $\overline{E1}$, E2).

E3 - An event: a withdrawal well into the Culebra Dolomite downgradient from the WIPP, or a simplified notation for a scenario in which event E3 occurs and other events do not ($\overline{TS}$, $\overline{E1}$, $\overline{E2}$, E3).

E1E2 - A scenario: intrusion of a borehole through a disposal panel into a pressurized brine occurrence in the Castile Formation (E1) and another intrusion of a borehole into the same panel (E2), without the occurrence of other events. Simplified notation for scenario $\overline{TS}$, E1, E2, $\overline{E3}$.

EDTA - Ethylenediaminetetraacetic acid: an organic compound that reacts with many metallic ions to form a soluble complex.

EEG - The Environmental Evaluation Group, an agency of the State of New Mexico that reviews the safety of the WIPP.

EID - Environmental Improvement Division

EIS - environmental impact statement

EPA - Environmental Protection Agency of the U.S. Government

ERDA - Energy Research and Development Administration

EXODUS - Computer program to format files for finite-element programs.

FASTQ - Computer program that generates finite element meshes.

FEIS - Final Environmental Impact Statement

50 FR 38066 - Federal Register, Volume 50, p. 38066

FORTLISTING - Computer program that lists programs and subroutines and summarizes comments and active FORTRAN lines.

FORTRAN - A computer programming language; from FORmula TRANslation.

40 CFR 191 - Code of Federal Regulations, Title 40, Part 191

FRP - fiberglass-reinforced plywood

FSAR - Final Safety Analysis Report

FSEIS - Final Supplement Environmental Impact Statement

GENESIS - Computer program to format files for finite-element programs.

GENMESH - Computer program that generates three-dimensional, finite difference, meshes.

GENNET - Computer program that generates networks.

GENPROP - Computer program for item entry into a property data base.

GRIDGEOS - Computer program that interpolates observational hydrologic or geologic data onto computational meshes.

HEPA - A High Efficiency Particulate Air filter usually capable of 99.97% efficiency as measured by a standard photometric test using a 0.3μm droplets (aerodynamic equivalent diameter) of DOP.

HLP2ABS - Computer program that reads a program help file and converts it into standard data base format from which the program abstract can be written.

HLW - high level waste

HST3D - Computer program that simulates three-dimensional ground-water flow systems and heat and solute transport.

ICRP - International Commission on Radiological Protection

IGIS - Interactive Graphics Information System

IMPES - implicit pressure, explicit saturation

INGRES - A relational data base management system used to implement the WIPP secondary property data base.

LHS - Latin hypercube sampling; computer program that selects Latin hypercube samples: A constrained Monte Carlo sampling scheme which samples n different values of a continuous random variate from n nonoverlapping intervals selected on the basis of equal probability.

MATSET - Computer program that sets material properties in CAMDAT.

MB139 - Marker Bed 139: One of 45 units within the Salado Formation composed of silica or sulfate and containing about 1 m of polyhalitic anhydrite and anhydrite. MB139 is located within the WIPP horizon.

MEF - Maximum Entropy Formalism

NAS - National Academy of Sciences

NCRP - National Council on Radiation Protection and Measurement

NEA - Nuclear Energy Agency of the Office of Economic Cooperation and Development, Paris.

NEFTRAN - Network Flow and TRANsport. Computer program that calculates flow and transport along one-dimensional legs comprising a flow network.

NRC - Nuclear Regulatory Commission

NWPA - Nuclear Waste Policy Act (Public Law 97-425 & 100-203)

PA - Performance Assessment

PATGEN - Computer program that transforms PATRAN to CAMDAT.

PCC/SRC - Computer program that calculates partial correlation and standardized regression coefficients.

pdf - Probability density function of a continuous random variate x is the derivative with respect to x of the cumulative distribution function (the probability that x takes on a value equal to or less than some specified value of x). The pdf is generically called a distribution.

POSTBOAST - Post-processor computer program (translator) for BOAST II.

POSTHST - Post-processor computer program (translator) for HST3D.

POSTLHS - Post-processor computer program (translator) for LHS.

POSTNEF - Post-processor computer program (translator) for POSTNEF.

POSTSECO - Post-processor computer program (translator) for SECO.

POSTSTAFF - Post-processor computer program (translator) for STAFF2D.

POSTSUTRA - Post-processor computer program (translator) for SUTRA.

POSTSWIFT II - Post-processor computer program (translator) for SWIFT II.

PREBOAST - Pre-processor computer program (translator) for BOAST II.

PREHST - Pre-processor computer program (translator) for HST3D.

PRELHS - Pre-processor computer program (translator) for LHS.

PRENEF - Pre-processor computer program (translator) for NEFTRAN.

PREPCC - Pre-processor computer program (translator) for PCC/SRC.

PRESTAFF - Pre-processor computer program (translator) for STAFF2D.

PRESTEP - Pre-processor computer program (translator) for STEPWISE.

PRESUTRA - Pre-processor computer program (translator) for SUTRA.

PRESWIFT II - Pre-processor computer program (translator) for SWIFT II.

QA - quality assurance

R_{acc} - Release of radioisotopes at the subsurface boundary of the accessible environment.

R_C - Release of radioisotope-bearing cuttings and eroded material to the land surface during drilling of an intrusion borehole.

RCRA - Resource, Conservation, and Recovery Act of 1976 (Public Law 94-580)

RH-TRU - Remote-Handled TRansUranic waste. Packaged TRU waste whose external surface dose rate exceeds 200 mrem per hour, but not greater than 1,000 mrem per hour.

ROOM - Computer program for a repository room simulation.

R_D - Release of radioisotope-bearing brine to the land surface through a withdrawal well in the Culebra Dolomite Member downgradient from the WIPP.

SAR - Safety Analysis Report

SECO - A computer program for calculating ground-water flow and transport with varying fluid densities.

SECO2D - Computer program for two-dimensional ground-water flow simulation.

SEIS - Supplement Environment Impact Statement

SNL - Sandia National Laboratories

STAFF2D - Computer program for a finite-element transport model.

STEPWISE - Computer program that performs stepwise regression including rank regression.

SUMMARIZE - Computer program that provides multiple CAMDAT summaries.

SUTRA - Finite-element simulation computer program that calculates saturated-unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically reactive single-species solute transport.

SUTRAW/G - SUTRA computer program modified for fluid as a gas instead of as a liquid.

SWB - standard waste box

SWIFT II - Sandia Waste-Isolation Flow and Transport computer program that simulates saturated flow and heat, brine, and radionuclide chain transport in porous and fractured media.

TC - A process included in scenario construction - Unexpected climatic change.

TRACKER - Computer program that tracks neutrally buoyant particles in a steady or transient flow.

TRU - TRansUranic

TS - An event used to develop scenarios: conventional or solution mining of potash outside the land withdrawal boundary that results in areas of subsidence, which act as areas of recharge to underlying aquifers; a simplified notation for a scenario in which TS occurs and other events do not ($\overline{TS}$, $\overline{E1}$, $\overline{E2}$, E3).

TXT2CAM - Computer program for ASCII to binary CAMDAT conversion.

UNSWIFT - Computer translator program that converts SWIFT II input files into CAMDAT.

WAC - Waste Acceptance Criteria

WEC - Westinghouse Electric Corporation

WIPP - Waste Isolation Pilot Plant

WPO - WIPP Project Office

Abbreviations and Symbols

Am - americium

atm - atmosphere

Ba - barium

Ce - cerium

Cf - californium

Ci - curies

cm - centimeter

Cm - curium

Co - cobalt

Cs - cesium

Cu - copper

Eh - oxidation potential

Eu - europium

Fe - iron

fm - formation

ft - foot

g - grams

gal - gallon

kg - kilogram(s)

km - kilometer(s)

ℓ - liter

lb - pound

m - meter(s)

M - Molar (molarity): Concentration of a solution expressed as moles of solute per liter of solution.

mg/ℓ - milligrams per liter

mi - mile(s)

μd - microdarcy

md - millidarcy

Mn - manganese

MPa - megapascal (10^6 Pa)

mrem - millirem (10^{-3} rem)

nCi - nanocuries

Ni - nickel

NM - New Mexico

Np - neptunium

Pa - pascal

Pb - lead

pH - the negative logarithm of the activity of hydrogen ion

Pr - praseodymium

Pu - plutonium

Ra - radium

Rn - radon

Ru - ruthenium

Sb - antimony

Si - silicon

Sm - samarium

Sr - strontium

Te - tellurium

Th - thorium

U - uranium

Y - yttrium

yr - year

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END

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