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Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991

Volume 1: Methodology and Results

WIPP Performance Assessment Division

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PRELIMINARY COMPARISON WITH 40 CFR PART 191, SUBPART B FOR THE WASTE ISOLATION PILOT PLANT, DECEMBER 1991

VOLUME 1: METHODOLOGY AND RESULTS

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ABSTRACT

Before disposing of transuranic radioactive wastes at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy must have a reasonable expectation that the WIPP will comply with the quantitative requirements of Subpart B of 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*. Sandia National Laboratories, through iterative performance assessments of the WIPP disposal system, is conducting an evaluation of the long-term performance of the WIPP that includes analyses for the Containment Requirements and the Individual Protection Requirements of Subpart B of the Standard. Recognizing that unequivocal proof of compliance with the Standard is not possible because of the substantial uncertainties in predicting future human actions or natural events, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed, qualitative judgment. Performance assessments of the WIPP will provide as detailed and thorough a basis as practical for the quantitative aspects of that decision.

The 1991 preliminary performance assessment is a snapshot of a system that will continue to evolve until a final compliance evaluation can be made. Results of the 1991 iteration of performance assessment are preliminary and are not suitable for final compliance evaluations because portions of the modeling system and data base are incomplete, conceptual model uncertainties are not fully included, final scenario probabilities remain to be determined, and the level of confidence in the results remains to be established. In addition, the final version of the EPA Standard, parts of which were remanded to the EPA in 1987 for further consideration, has not been promulgated. Results of the 1991 preliminary performance assessment do not indicate potential violations of Subpart B of the Standard and support the conclusion based on previous analyses, including the 1990 preliminary performance assessment, that reasonable confidence exists that compliance with Subpart B of the Standard can be achieved.

ACKNOWLEDGMENTS

The WIPP Performance Assessment Division is comprised of both Sandia and contractor employees working as a team to produce these annual preliminary comparisons with EPA regulations, assessments of overall long-term safety of the repository, and interim technical guidance to the program. The on-site team, affiliations, and contributions to the 1991 performance assessment are listed in alphabetical order:

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The foundation of the annual WIPP performance assessment is the underlying data set and understanding of the important processes in the engineered and natural barrier systems. The SNL Nuclear Waste Technology Department is the primary source of these data and understanding. Assistance with the waste inventory comes from WEC and its contractors. We gratefully acknowledge the support of our departmental and project colleagues. Some individuals have worked closely with the performance assessment team, and we wish to acknowledge their contributions individually:

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API = Applied Physics Incorporated
ASU = Arizona State University
ECO = Ecodynamics Research Associates
EPE = Epoch Engineering
GC = Geo-Centers Incorporated
IT = International Technology
ReS = ReSpec
SAI = Scientific Applications International Corporation
SNL = Sandia National Laboratories
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PREFACE

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). Assessing compliance with the long-term performance criteria of Subpart B 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), is a cornerstone for the DOE's successful implementation of a TRU-waste disposal system.

This report (the *1991 Preliminary Comparison*) is a preliminary version of the planned document, *Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant* (the *Comparison*). The *1991 Preliminary Comparison* is the second in a series of annual "Performance Analysis and DOE Documentation" reports shown in the timing for performance assessment in the 1991 DOE report *Strategy for the Waste Isolation Pilot Plant Test Phase* (DOE/EM/48063-2). 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 the final report scheduled for 1996 (DOE/EM/48063-2). This report is a preview of the final *Comparison* 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 the 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 the resultant methodology reported here do not reflect the EPA's efforts to develop a new Subpart B.

The *1991 Preliminary Comparison* is based on last year's reports: the *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990* (SAND90-2347), *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)* (SAND89-2408), and *Sensitivity Analysis Techniques and Results for Performance Assessment at the Waste Isolation Pilot Plant* (SAND90-7103). The *1991 Preliminary Comparison* consists of four volumes. Volumes 2 (Probability and Consequence Modeling) and 3 (Reference Data) will be published in December 1991 with this volume (Methodology and Results). Volume 4 (Uncertainty and Sensitivity Analyses) will be published in March 1992.

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

Vertical change bars in the right margins of Volume 1 of the *1991 Preliminary Comparison* indicate changes from the text published in the single-volume *1990 Preliminary Comparison*. Chapters 3 through 7 and Chapters 10 and 11 of the 1991 report, however, have been substantially revised or rewritten since the 1990 version and do not contain change bars. Chapters 3, 4, and 5 have been revised to reflect additions to the methodology and data used in evaluating the WIPP. Chapters 6 and 7 contain the results of the 1991 preliminary performance-assessment calculations. Chapters 10 and 11 discuss the 1991 results and summarize the status of the work to be completed to develop an adequate basis for evaluating compliance with Subpart B of the Standard.

Volumes 2, 3, and 4 do not contain change bars. Volume 2 is a compilation of essentially new material or material that was presented in a briefer form in 1990. Volume 3 is based on *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*, SAND89-2408, but contains numerous additions and refinements to the reference data base. Volume 4 reports the results of the uncertainty and sensitivity analyses for the 1991 calculations. Sensitivity analyses identify aspects of the modeling system that have the greatest potential to affect performance, thereby helping guide ongoing research. Because new data or new interpretations of existing data may change the conceptual models and/or the ranges and distributions of parameters throughout the life of the WIPP Project, sensitivity analyses are also iterative. Volume 4 is substantially revised and rewritten compared to the previous year's report, *Sensitivity Analysis Techniques and Results for Performance Assessment at the Waste Isolation Pilot Plant*, SAND90-7103.

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. The process is dynamic, however, and both the results and the description of the system are in part already out of date. In addition, data used in the 1991 performance assessment were accepted through July 1, 1991. This report presents a snapshot of a system that will continue to evolve until the final *Comparison* is complete.

The final *Comparison*, which will provide both quantitative and qualitative input to the determination of WIPP compliance with 40 CFR Part 191, Subpart B, will be without precedent as a completed performance evaluation for this type of geologic repository. Therefore, careful planning is required to assure that the final *Comparison* will be adequate to support the determination of compliance. Coordination among the performance-assessment team at Sandia National Laboratories; the DOE WIPP Project Site Office (Carlsbad, New Mexico), WIPP Project Integration Office (Albuquerque, New Mexico), and Headquarters; the WIPP Panel of the National Research Council's Board on Radioactive Waste Management; the New Mexico Environment Department; the Environmental Evaluation Group; and the EPA is extremely important prior to preparation of the final *Comparison*. The draft of the final *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 1991 DOE report *Strategy for the Waste Isolation Pilot Plant Test Phase* (DOE/EM/48063-2) outlines possible procedures that may be followed prior to the final determination of WIPP compliance. The DOE's decision process for the WIPP will involve all the activities necessary to document compliance with the applicable regulations, to complete the necessary institutional interactions, and to prepare a summary statement and recommendation for the Secretary of Energy upon which a final determination of compliance can be based. Additional documentation other than that required for compliance with Subpart B of 40 CFR Part 191 will be needed for the Resource Conservation and Recovery Act (RCRA), the National Environmental Policy Act (NEPA), and applicable Federal and State regulations. All of these documents will be reviewed by the cognizant DOE organizations whose concurrence is needed. The purpose of the review is to ensure that the analysis and documentation are adequate and appropriate to support the determination of compliance, to obtain the necessary permits and approvals, and to comply with DOE orders.

Once the process of documentation and review (both internal and external) has been completed, the DOE will prepare an internal summary report for the Secretary of Energy. This report will include a recommendation as to whether waste disposal at the WIPP should begin. Given a determination of compliance with the applicable regulations, a favorable record of decision on a new supplemental environmental impact statement, and a favorable readiness review, the Secretary will decide whether the WIPP should begin receiving TRU waste for permanent disposal. If land-withdrawal legislation mandates or the DOE signs with another agency a memorandum of understanding that provides for an independent certification of the DOE's compliance determination, the decision process will be amended.

This *1991 Preliminary Comparison* provides an opportunity for interested parties to monitor the WIPP performance assessment and give constructive input for future annual iterations and the final *Comparison*.

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is a research and development project of the United States Department of Energy (DOE). The WIPP is designed to be the first mined geologic repository to demonstrate the safe disposal of transuranic (TRU) radioactive wastes generated by DOE defense programs since 1970. Before disposing of radioactive waste at the WIPP, the DOE must have a reasonable expectation that the WIPP will comply with the quantitative requirements of Subpart B of the United States Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (40 CFR Part 191, U.S. EPA, 1985), referred to in this report 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.

Performance assessment as defined for the Containment Requirements of Subpart B of 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)). As used in this report, performance assessment includes analyses for predicting doses as well as the definition in the Standard, because the methodology developed for predicting releases for the Containment Requirements can be used for predicting doses for the Individual Protection Requirements.

Recognizing that unequivocal proof of compliance with the Standard is not possible because of the substantial uncertainties in predicting future human actions or natural events, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed, qualitative judgment. Performance assessments of the WIPP will provide as detailed and thorough a basis as practical for the quantitative aspects of that decision. Performance assessments will provide quantitative, probabilistic analyses of disposal-system performance for comparison with the regulatory limits. However, the three quantitative requirements in Subpart B specify that the disposal system design must provide a <u>reasonable expectation</u> that the various quantitative tests can be met. Specifically, the qualitative nature of the EPA's approach is established in the Containment Requirements of the Standard: what is required is a reasonable expectation, on the basis of the record before the DOE, that compliance with the Containment Requirements will be achieved.

Sandia National Laboratories (SNL), as the scientific program manager for the WIPP, is responsible for developing an understanding of the processes and systems that affect long-term isolation of wastes in the WIPP and applying that understanding to evaluation of the long-term WIPP performance and compliance with the Standard. SNL defines and implements experiments both in the laboratory and at the WIPP, develops and applies models to interpret the experimental data, and develops and applies performance-assessment models. This report summarizes SNL's late-1991 understanding of the WIPP Project's ability to quantitatively evaluate compliance with the long-term performance requirements set by Subpart B of the Standard. It documents one in a series of annual iterations of performance assessment: each iteration builds on the previous year's work until a final, defensible compliance evaluation can be made. Results of this preliminary performance assessment should not be formally compared to the requirements of the Standard to determine whether the WIPP disposal system complies with Subpart B. The disposal system is not adequately characterized, and necessary models, computer programs, and data bases are incomplete. Furthermore, Subpart B of the Standard was vacated in 1987 by a Federal Court of Appeals and remanded to the EPA for reconsideration.

Instead of presenting a formal compliance evaluation, this report examines the adequacy of the available information for producing a comprehensive comparison to the Containment Requirements and the Individual Protection Requirements of the 1985 Standard, in keeping with the Consultation and Cooperation Agreement (as modified) between the DOE and the State of New Mexico. Defensibility of the compliance evaluation ultimately will be determined in part by qualitative judgment, on the basis of the record before the DOE, regarding reasonable expectations of compliance, assuming that concept is retained by the EPA in repromulgating Subpart B.

Adequate documentation and independent peer review are essential parts of a performance assessment, without which informed judgments of the suitability of the 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.

Compliance-Assessment Overview

A performance assessment must determine the events that can occur, the likelihood of these events, and the consequences of these events. The WIPP performance assessment is, in effect, a risk assessment. Risk can be represented as a set of ordered triples. The first element in each triple describes things that may happen to the disposal system in the future (i.e., the scenarios). The second element in each triple describes how likely these things are to happen (i.e., scenario probability). The third element in each triple describes the consequences of the occurrences associated with the first element (i.e., EPA normalized releases of radionuclides to the accessible environment).

An infinite number of possible 10,000-year histories of the WIPP exist. These possible histories are grouped into summary scenarios for probability assignment and consequence analysis. To increase resolution in the evaluation, the summary scenarios involving human intrusion into the repository are further decomposed into computational scenarios. For the 1991 performance assessment, computational scenarios are distinguished by the time and number of intrusions, whether or not a brine reservoir is encountered below the waste, and the activity level of waste intersected. Probabilities are based on the assumption that intrusion boreholes are random in time and space (Poisson process) with a rate constant that is sampled as an uncertain parameter in the 1991 calculations.

The models used in the WIPP performance assessment exist at four different levels. Conceptual models characterize the understanding of the system. An adequate conceptual model is essential both for the development of the possible 10,000-year histories for the WIPP and for the division of these possible histories into the summary scenarios. Mathematical models are developed to represent the processes of the conceptual model. The mathematical models are predictive in the sense that, given known properties of the system and possible perturbations to the system, they project the response of the system conditional on modeling assumptions made during development. Numerical models are developed to provide approximations to the solutions of the mathematical models. Computer models implement the numerical models and actually predict the consequences of the occurrences associated with the scenarios.

As uncertainties will always exist in the results of a performance assessment, the impact of these uncertainties must be characterized and displayed. Thus, sensitivity and uncertainty analyses are an important part of a performance assessment. Sensitivity analysis determines the importance of specific components or subsystems to the results of the consequence analyses. Uncertainty analysis determines how imprecise knowledge about the disposal system affects confidence in the results of the consequence analysis. Uncertainty in the results of the risk analysis may result from the completeness of the occurrences considered, the aggregation of the occurrences into scenarios for analysis, the selection of models (at all four levels above) and imprecisely known parameters for use in the models, and stochastic variation in future occurrences.

Many techniques are available for uncertainty and sensitivity analysis. The WIPP performance assessment uses Monte Carlo analysis techniques. A Monte Carlo analysis involves five steps: selection of variable ranges and distributions; generation of a sample from the parameter value distributions; propagation of the sample through the analysis; analysis of the uncertainty in results caused by variability in the sampled parameters; and sensitivity analyses to identify those parameters for which variability in the sampled value had the greatest effect on the results.

No single summary measure can adequately display all the information produced in a performance assessment. Thus, decisions on the acceptability of the WIPP should be based on a careful consideration of all available information rather than on a single summary measure. Complementary cumulative distribution functions (CCDFs) are used to display information on scenario probability and consequence. Uncertainty resulting from imprecisely known parameter values results in a family of CCDFs. Conceptual model uncertainty has not yet been adequately addressed in any performance assessment but could be included through the set of imprecisely known variables or by separate performance assessments for each alternative conceptual model. This will be addressed in future annual performance assessments. Variability in the family of CCDFs can be displayed by showing the entire family or by showing the mean and selected quantile curves. For human-intrusion scenarios of WIPP performance, CCDFs will be compared to the limits set in the Containment Requirements of the Standard.

Results

As previously indicated, compliance with the Containment Requirements will be evaluated using a family of CCDF curves that graph exceedance probability versus cumulative radionuclide releases for all significant scenarios. All results are preliminary and are not suitable for final compliance evaluations because portions of the modeling system and data base are incomplete, conceptual model uncertainties are not fully included, final scenario probabilities remain to be determined, the final version of the EPA Standard has not been promulgated, 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 data base.

Simulations of undisturbed performance indicate zero releases to the accessible environment in the 10,000 years of regulatory concern for the Containment Requirements. Because no releases are estimated to occur in the 10,000-year regulatory period for undisturbed performance, the base-case summary scenario is not analyzed, but it is included in CCDF construction through its estimated probability and zero consequences.

For the 1991 performance assessment, the factors used to define the computational scenarios are time and number of intrusions, whether or not a brine reservoir is encountered below the waste, and activity level of the waste intersected. Drilling intrusions are assumed to follow a Poisson process. The rate constant is an imprecisely known variable with the upper bound defined by the EPA Standard as 30 boreholes/km^2/10,000 years and lower bound of zero. For this performance assessment, the regulatory time interval of 10,000 years is divided into five disjoint time intervals of 2000 years each, with intrusion occurring at the midpoints of these intervals (at 1000, 3000, 5000, 7000, and 9000 years). An uncertain area fraction of the waste panels is assumed to be underlain by a pressurized brine reservoir in the Castile Formation. Four activity levels for CH waste and one activity level for RH waste are defined and their distributions sampled to represent variability in the activity level of waste penetrated by a drilling intrusion.

For the 1991 performance assessment, 45 imprecisely known parameters were sampled for use in consequence modeling for the Monte Carlo simulations of repository performance. For each of these 45 parameters, a range and distribution was subjectively assigned based on available data. These parameters specify physical, chemical, and hydrologic properties of the geologic and engineered barriers. Parameters for climatic variability and future drilling intrusions are also included.

Important differences between the 1990 and 1991 Monte Carlo analyses are the inclusion in the 1991 modeling of a two-phase (brine and gas) flow computer code that allows examining effects of waste-generated gas in uncertainty and sensitivity analyses, the addition of parameters related to dual porosity (both chemical and physical retardation) in the Culebra, the use of a set of conditional simulations for transmissivity in the Culebra instead of the simple zonal approach of the 1990 performance assessment, and the inclusion of a preliminary analysis of potential effects of climatic variability on flow in the Culebra. Distributions for parameter values for radionuclide solubility in repository brine and radionuclide retardation in the Culebra were based on judgment from expert panels.

Latin hypercube sampling is used to incorporate parameter uncertainty into the performance assessment. A Latin hypercube sample of size 60 was generated from the set of 45 variables. After the sample was generated, each element of the sample was propagated through the system of computer codes used for analysis of human-intrusion scenarios. Each sample was used in the calculation of both cuttings/cavings and subsurface groundwater releases for intrusion times of 1000, 3000, 5000, 7000, and 9000 years. Two types of intrusions were examined: those involving penetration of one or more boreholes to or through a waste-filled room or drift in a panel without intersecting pressurized brine below, and those involving penetration of exactly two boreholes to or through a waste-filled room or drift in a panel, with one borehole also intersecting a pressurized brine reservoir below. Consequences of intrusions involving penetration of one or more boreholes through a waste-filled room or drift in a panel and into a pressurized brine reservoir were found to be similar to and bounded by the second type of intrusions.

Except for a few low-probability releases, cuttings/cavings dominate the CCDFs for total releases. Based on the performance-assessment data base and present understanding of the WIPP disposal system, the summary CCDF curves showing exceedance probability versus total cumulative normalized releases to the accessible environment resulting from both groundwater transport in the subsurface and releases at the surface during drilling are the preferred choice for preliminary comparison with the Containment Requirements. These preliminary summary curves were generated including the effects of waste-generated gas, dual-porosity transport in the Culebra, and a preliminary estimate of changes in recharge caused by climatic variability, and are considered to be the most realistic choice for an informal comparison with the Containment Requirements. Informal comparison of these preliminary results with the Containment Requirements indicates that, for the assumed models, parameter values, and scenario probabilities, summary CCDFs (mean and median curves) lie an order of magnitude or more below the regulatory limits.

Conclusions

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

- **Containment Requirements**. As previously noted, results presented in this report are preliminary and are not suitable for evaluating compliance with the Containment Requirements of the Standard. As explained in more detail in Chapter 11, portions of the modeling system and the data base are incomplete, conceptual model uncertainties are not fully included, final scenario probabilities remain to be estimated, and the level of confidence in the results has not been established. In addition, the Standard has not been repromulgated since its 1987 remand.

  Informal comparison of these preliminary results with the Containment Requirements indicates that, for the assumed models, parameter values, and scenario probabilities, summary CCDFs (mean and median curves) lie an order of magnitude or more below the regulatory limits.

- **Assurance Requirements.** Plans for implementing the first two Assurance Requirements (Active Institutional Controls and Monitoring) are preliminary. The design for passive institutional controls is currently being considered by an expert panel. Implementation of passive institutional controls can occur only after their design has been selected. Barrier design is an integral part of the SNL research effort. The WIPP Project has satisfied the natural resources requirement and has published a summary report to that effect. The EPA stated in the Standard that current plans for mined geologic repositories meet the waste removal requirement without additional design.

- **Individual Protection Requirements.** Previous and current evaluations of undisturbed performance at the WIPP have indicated that no releases to the accessible environment will occur within 10,000 years. Dose predictions are therefore not expected to be required for the 1000-year period specified by the Individual Protection Requirements. However, as with the Containment Requirements, formal comparison to the Standard cannot be prepared until the bases of the compliance-assessment system are judged adequate.

- **Groundwater Protection Requirements.** Studies have determined that no groundwater near the WIPP meets the criteria for "special source of ground water" as specified in the Standard. Based on the 1985 Standard, the Groundwater Protection Requirements are not relevant to the WIPP disposal system. No further action should be necessary.

1. INTRODUCTION

[NOTE: The text of Chapter 1 is followed by a synopsis that summarizes essential information, beginning on page 1-29.]

Before disposing of radioactive waste at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy (DOE) must have a reasonable expectation that the WIPP will comply with the quantitative requirements of Subpart B of the United States Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (40 CFR Part 191; U.S. EPA, 1985), referred to herein as the Standard (included as Appendix A of this volume). 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 *Comparison with 40 CFR, Part 191, Subpart B, for the Waste Isolation Pilot Plant*. The planned scope of that document includes the final report for the performance assessment of the WIPP disposal system and relevant data for determining whether to proceed with disposal at the WIPP.

1.1 40 CFR Part 191, The Standard (1985)

The Standard promulgated in 1985 by the EPA is divided into two subparts (Figure 1-1). 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 nonmandatory guidance for implementing Subpart B. The *Compliance Strategy* (U.S. DOE, 1989a) 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

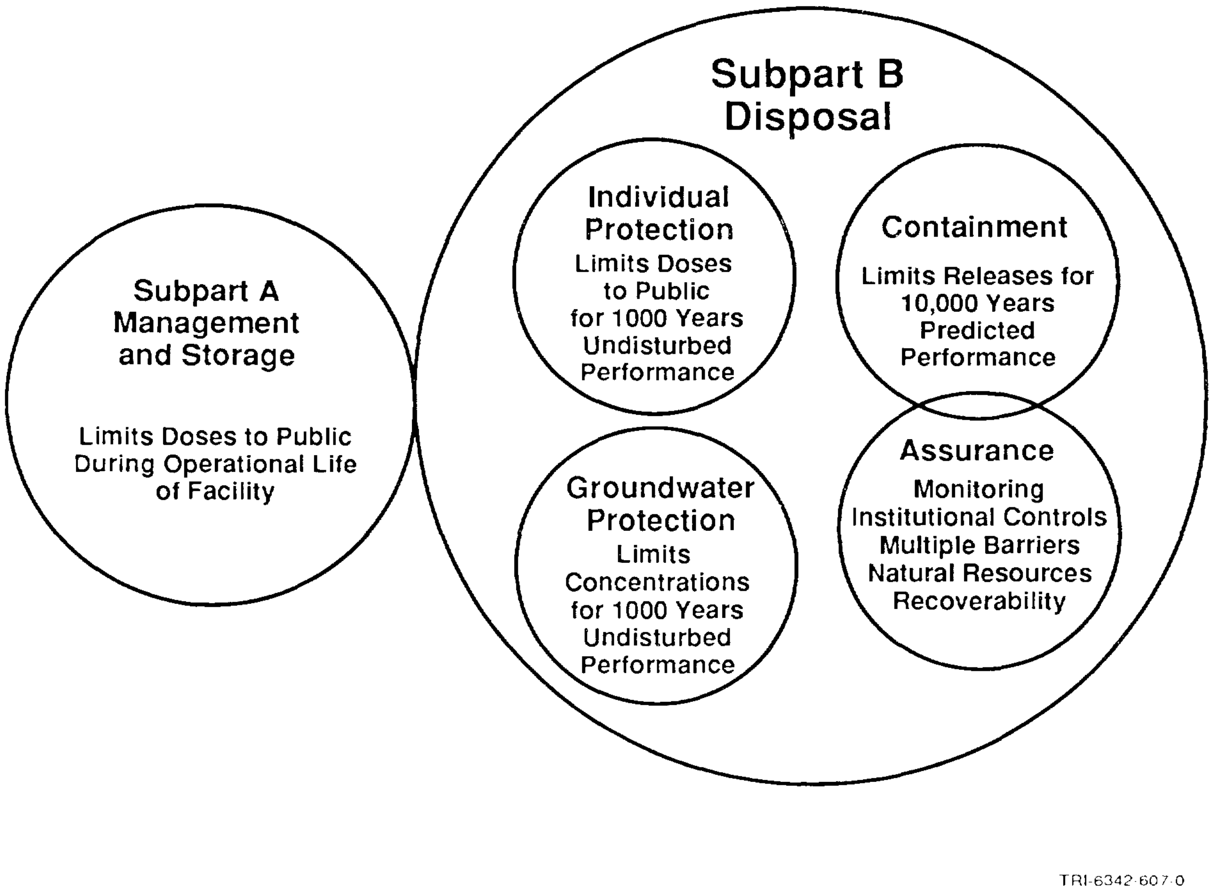

Figure 1-1. Graphical Representation of 40 CFR Part 191 Environmental Standards for Management and Disposal of Spent Fuel, High-Level, and Transuranic Waste (after U.S. DOE, 1989a).

"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, 1989a; also see U.S. DOE, 1989a).

1.1.1 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. Working Draft 3, a proposed revison of the Standard, was prepared for discussion within the EPA in April 1991. A repromulgated Standard is not expected before mid-1993. The Second Modification to the Consultation and Cooperation Agreement (U.S. DOE and State of New Mexico, 1981, as modified) commits the WIPP Project to proceed with compliance planning 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 repromulgation.

1.1.2 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 and 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 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 1-2. 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 proposed 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, 1990a) 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, 1989a). The boundary indicated as "WIPP" on illustrations in this volume is the boundary of the proposed land-withdrawal area.

The DOE compliance approach to the Standard is described in the WIPP *Compliance Strategy* (U.S. DOE, 1989a; also see Bertram-Howery and Hunter, 1989a 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 the 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.

1.1.3 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 2. The Containment Requirements (§ 191.13(a)) necessitate probabilistically predicting cumulative releases for 10,000 years. The Individual Protection Requirements (§ 191.15) set limits on 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 1,000 years. Some necessary definitions and interpretations are given below.

Controlled Area

The controlled area as defined in Subpart B of the Standard is

> (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and

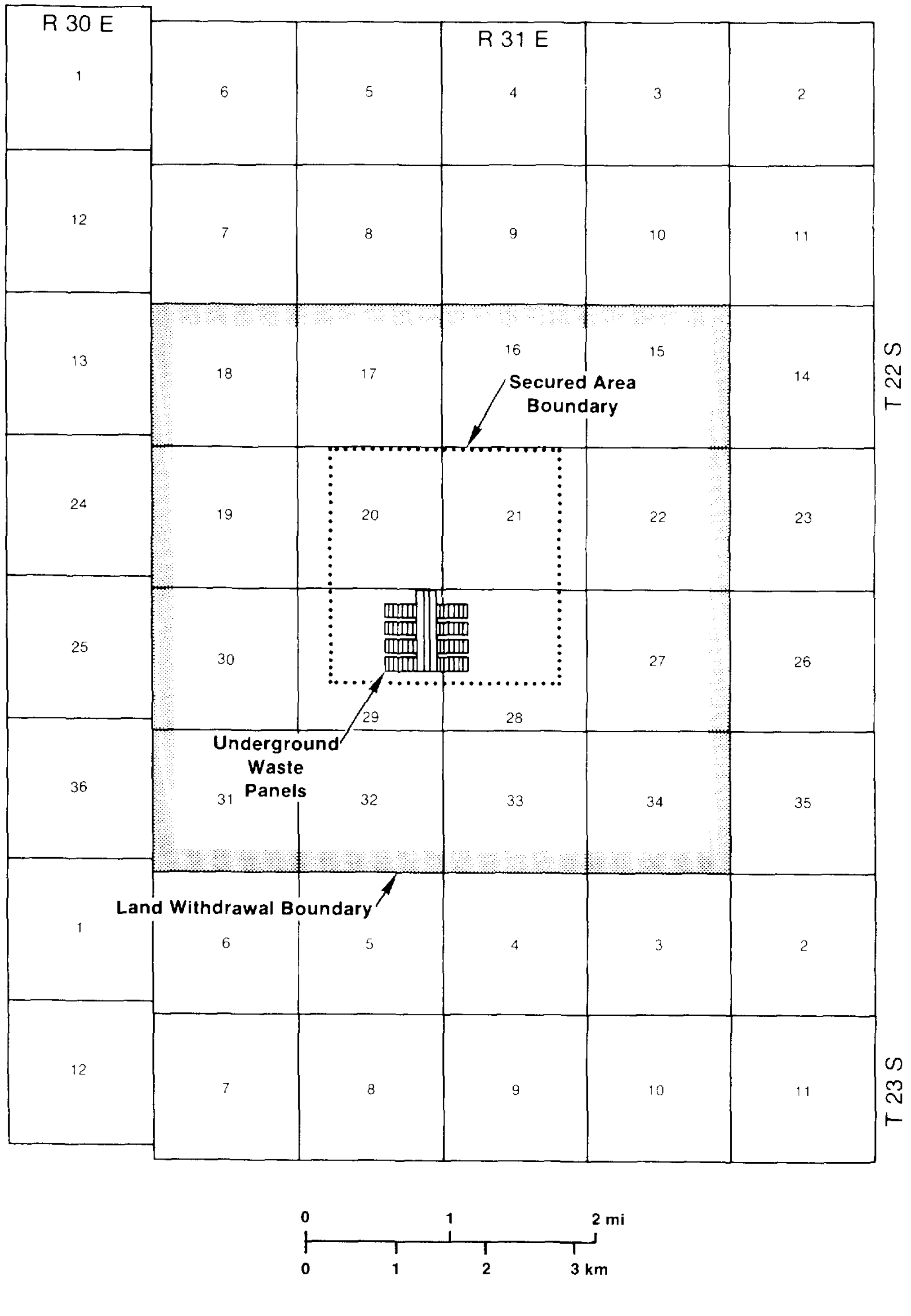

Figure 1-2. Position of the WIPP Waste Panels Relative to WIPP Boundaries and Surveyed Section Lines (U.S. DOE, 1989a).

> 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 (§ 191.12(g)).

The controlled area 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 secured area boundary (Figure 1-2) or with the boundary proposed in legislation pending before Congress for the WIPP land withdrawal (Figure 1-3). 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)). According to this definition, the surface of the controlled area is in the accessible environment; the underlying subsurface of the controlled area is not part of the accessible environment (Figure 1-3). 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. The "site" for the purposes of Subpart A and the "disposal site" for the purposes of Subpart B are not the same. For the purposes of the WIPP strategy for compliance with Subpart B, the disposal site and the controlled area are 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 1-3). 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 include permanent markers placed at a disposal site, along with records, government ownership, and other methods of preserving knowledge about the disposal system. 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); § 191.12(g)).

"Reasonable Expectation" of Compliance

The EPA discusses the overall approach of the Standard in a preamble to the regulations. The three quantitative requirements in Subpart B specify that the disposal system design must provide a "reasonable expectation" that their

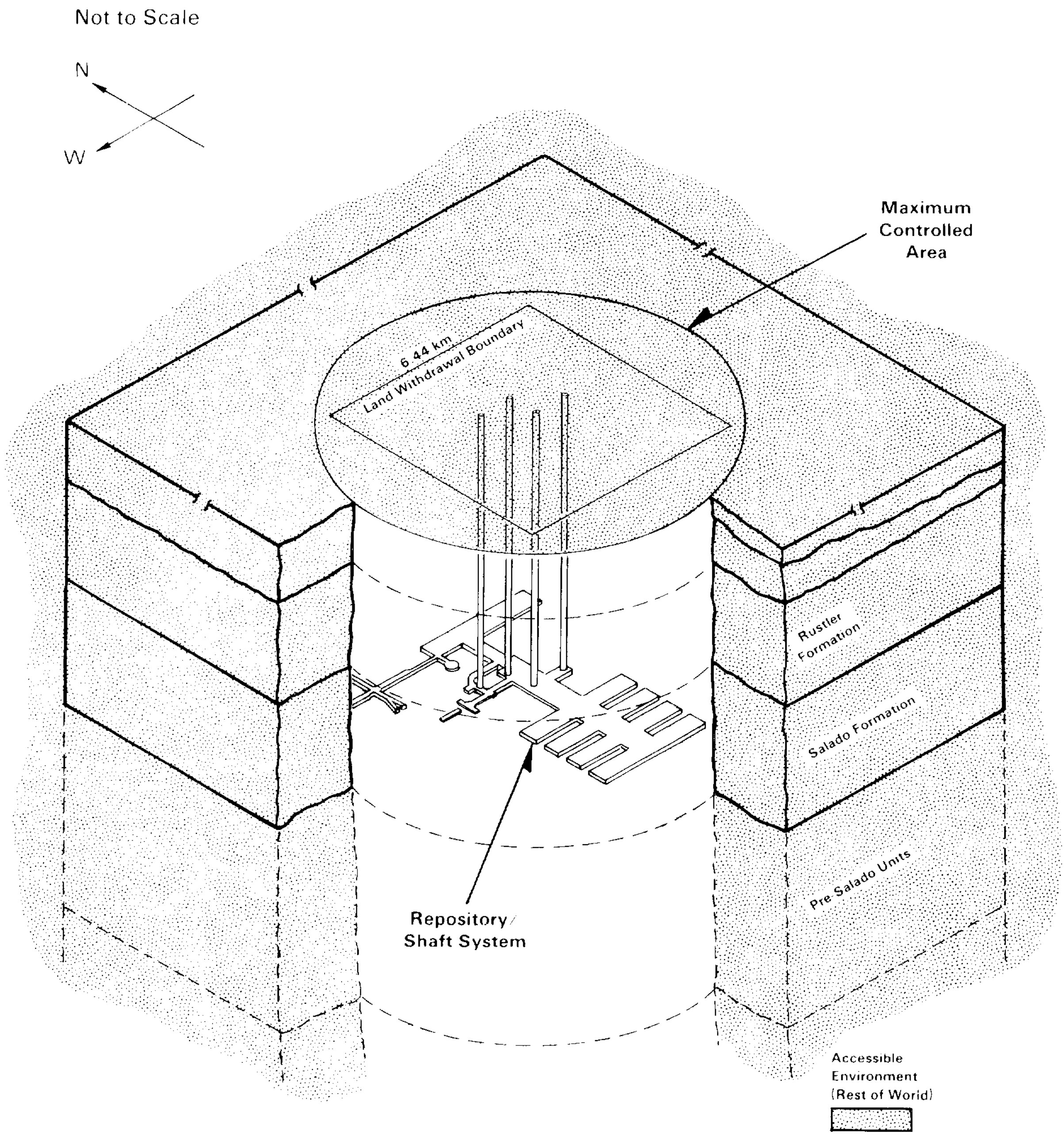

Figure 1-3. Artist's Concept Showing the Two Components of the WIPP Disposal System: Controlled Area and Repository/Shaft System. The repository/shaft system scale is exaggerated. The proposed land-withdrawal boundary is shown at the same scale as the maximum extent of the controlled area (Bertram-Howery and Hunter, 1989b).

various quantitative tests can be met. In the preamble, the EPA states that this test of qualitative judgment is meant 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 isolation while allowing the [DOE] adequate flexibility to handle specific uncertainties that may be encountered" (U.S. EPA, 1985, p. 38077).

In the preamble to the Standard, the EPA states that it clearly intends qualitative considerations to have equal importance with quantitative analyses in determining compliance with Subpart B (U.S. EPA, 1985, p. 38066). The EPA states 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). The EPA also states 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 intends 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] believe[s] 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:

> 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 preamble to 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 that too many opportunities for errors in calculations or judgments are possible 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" (§ 191.14).

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, 1987, currently in revision) that will be implemented and on the qualitative judgment of the DOE and its analysts. The preceding discussion 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.

1.2 Application of Additional Regulations to the WIPP

In addition to 40 CFR Part 191, the Resource Conservation and Recovery Act (RCRA) and the National Environmental Policy Act (NEPA) are considered in an overall evaluation of the WIPP as a repository for TRU wastes. This report does not provide an evaluation of the WIPP in regard to these additional regulations. However, the two regulations are briefly discussed as part of the overview of the WIPP.

1.2.1 RCRA

The Resource Conservation and Recovery Act (RCRA) was enacted in 1976 to provide management of hazardous waste. In July 1990 the EPA authorized the State of New Mexico to apply the RCRA regulations to facilities in the state that managed radioactive mixed waste. In March 1989 the DOE had petitioned the EPA for a "no migration" determination for the WIPP Test Phase. The DOE submitted models to demonstrate, to a reasonable degree of certainty, that the emplaced waste would not migrate from the disposal unit during the WIPP Test Phase. The EPA issued a conditional "no migration" determination, for the WIPP Test Phase only, in November 1990. Strategies are currently being developed for RCRA compliance after the Test Phase is completed.

1.2.2 NEPA

The National Environmental Policy Act (NEPA) (42 USC 4321 et seq.) of 1969 requires all agencies of the Federal Government to prepare a detailed statement on the environmental impacts of proposed "major Federal actions significantly affecting the quality of the human environment." In compliance with NEPA, the DOE has published the *Draft Environmental Impact Statement, Management of Commercially Generated Radioactive Waste* (U.S. DOE, 1979), the *Final Environmental Impact Statement: Waste Isolation Pilot Plant* (FEIS) (U.S. DOE, 1980a), and the *Final Supplement Environmental Impact Statement, Waste Isolation Pilot Plant* (FSEIS) (U.S. DOE, 1990c). An additional supplemental environmental impact statement is planned prior to permanent disposal at the WIPP (U.S. DOE, 1991a).

1.3 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, 1990b).

The *1991 Preliminary Comparison* report is organized into four volumes. Volume 1 (this volume) contains the methodology and results for the 1991 preliminary performance assessment. Volume 2 describes the consequence and probability models used and contains the 1991 computational data base. Volume 3 is the 1991 reference data base. Volume 4 contains techniques and results of the uncertainty and sensitivity analyses for the 1991 performance assessment. Volumes 2 and 3 are published concurrently with Volume 1 (this volume); Volume 4 will be published 3 months after Volumes 1 through 3. The results presented in Volume 4 will be used to guide subsequent performance assessments.

Because this report is a preliminary version of the final report, many sections are preliminary or incomplete. In Volume 1 (this volume), brief descriptions of the Standard and the WIPP Project are provided in Chapter 1. Chapter 2 discusses application of Subpart B of the Standard to the WIPP disposal system. Chapter 3 provides an overview of the compliance-assessment methodology for the WIPP Project. Chapter 4 identifies and describes the scenarios being used in the compliance assessment. Chapter 5 describes the components of the compliance-assessment system. Chapter 6 presents the results of the second preliminary performance assessment relative to the Containment Requirements (§ 191.13) of the Standard. Chapter 7 describes results relative to the Individual Protection Requirements (§ 191.15) of the Standard. Chapter 8 describes plans for implementing the Assurance Requirements (§ 191.14) of the Standard. Chapter 9 discusses the relevance of the Groundwater Protection Requirements (§ 191.16) of the Standard to the WIPP. Chapter 10 considers the adequacy of the computational bases for the assessment. Chapter 11 identifies the status of the 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 contains comments from the New Mexico Environment Department (NMED) and the Environmental Evaluation Group (EEG) on the *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Plant, December 1990* (SAND90-2347), and the performance-assessment team's responses to those comments.

The final *Comparison* will be reviewed extensively. The planned organization of the final *Comparison* includes an appendix similar to Appendix B of this report that will present 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 (B) 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.

1.4 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.

1.4.1 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 the 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 for the Test Phase (U.S. DOE, 1989a). "Disposal," as defined in the Standard, will occur when the mined repository is sealed and decommissioned.

1.4.2 PARTICIPANTS

The DOE is the implementing agency, as defined in the Standard, for the WIPP Project. The WIPP Project is managed by the DOE WIPP Project Integration Office (Albuquerque, New Mexico) through the DOE WIPP Project Site Office in Carlsbad, New Mexico. The WIPP Project Site Office is assisted by two prime contractors: Westinghouse Electric Corporation (WEC) and Sandia National Laboratories (SNL). The operating contractor is responsible for all facility operations 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 the scientific program manager for the WIPP, is responsible for developing an understanding of the processes and systems that affect long-term isolation of wastes in the WIPP and applying that understanding to evaluate the long-term WIPP performance and compliance with the Standard. SNL defines and implements experiments both in the laboratory and at the WIPP, develops and applies models to interpret the experimental data, and develops and applies performance-assessment models (U.S. DOE, 1991b).

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 New Mexico Environment Department (NMED), 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, and the Defense Nuclear Facilities Safety Board. The EPA maintains a dialog with the WIPP Project concerning the *Preliminary Comparison* reports. The WIPP also receives close public scrutiny. Finally, the National Defense Authorization Act, Fiscal Year 1989 (Public Law 100-456) assigned the Environmental Evaluation Group (EEG) to the New Mexico Institute of Mining and Technology, with the responsibility for independent technical evaluation of the WIPP with regard to the protection of public health and safety and the protection of the environment.

1.4.3 PHYSICAL SETTING

The characteristics of the WIPP are described in detail in the FEIS (U.S. DOE, 1980a), Lappin et al. (1989), the WIPP *Final Safety Analysis Report* (FSAR) (U.S. DOE, 1990a), the FSEIS (U.S. DOE, 1990c), Brinster (1991), and Beauheim et al. (1991). Additional detailed discussion in the *1991 Preliminary Comparison* is in Chapter 5 of this volume and in Volume 2. The WIPP (Figure 1-4) is in southeastern New Mexico, about 42 km (26 mi) east of Carlsbad, the nearest major population center (pop. 25,000 in the 1990 U.S. census). The area surrounding the WIPP has a small 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 about 5.6 km (3.5 mi) south of the WIPP surface facility (U.S. DOE, 1990a).

The surface of the land within the proposed land-withdrawal boundary has been leased for cattle grazing. At present, none of the ranches within ten miles use well water for human consumption because the water contains large concentrations of total dissolved solids. Drinking water for the WIPP is supplied by pipeline from wells about 30 mi (48 km) north of the area (U.S. DOE, 1990a).

Potash, oil, and gas are the only known important mineral resources. The volumes and locations of these resources are estimated in the FEIS for the

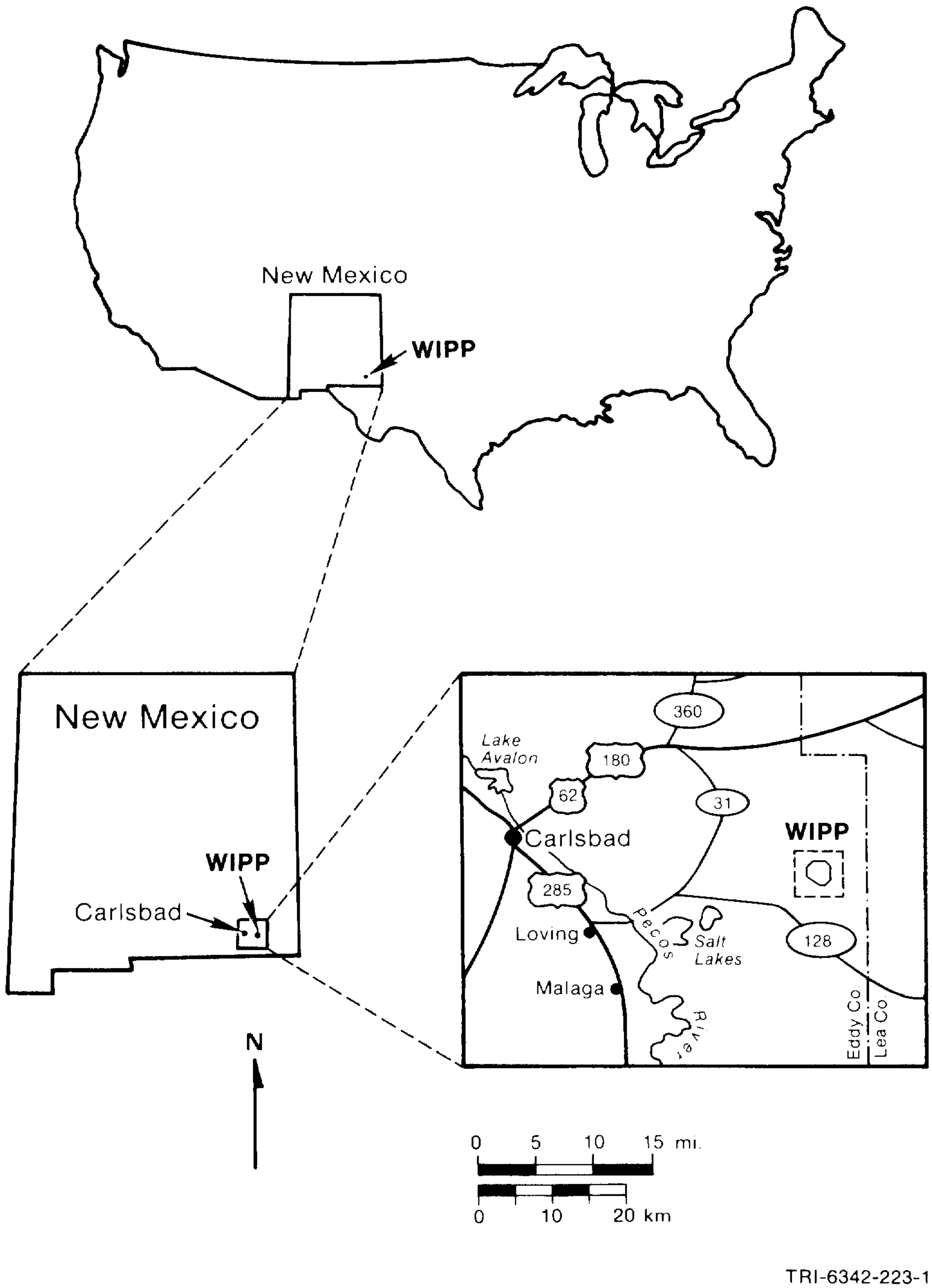

Figure 1-4. WIPP Location Map (after Bertram-Howery and Hunter, 1989a).

WIPP (U.S. DOE, 1980a). The surrounding area is used primarily for grazing, potash mining, and hydrocarbon exploration and production.

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. The surface location of the well, which is capable of producing gas, is outside the proposed land-withdrawal boundary, but the borehole is slanted to withdraw gas from rocks within the boundary. Except for this well, resource extraction is not allowed within the proposed land-withdrawal boundary.

Three potash mines and two associated chemical processing plants are between 8 and 16 km (5 and 10 mi) away. Potash mining is possible within a radius of 3 to 8 km (2 to 5 mi) (U.S. DOE, 1990a). The potash zone is about 137 m (450 ft) thick and is encountered about 457 m (1,500 ft) below the surface (Figure 1-5).

The WIPP is in the Delaware Basin between the high plains of West Texas and the Guadalupe Mountains of southeastern New Mexico. Prominent topographic features in the area are Los Medaños ("The Dunes"), Nash Draw, Laguna Grande de la Sal, and the Pecos River (Figures 1-6 and 1-7).

Los Medaños is a region of gently rolling sand dunes 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.

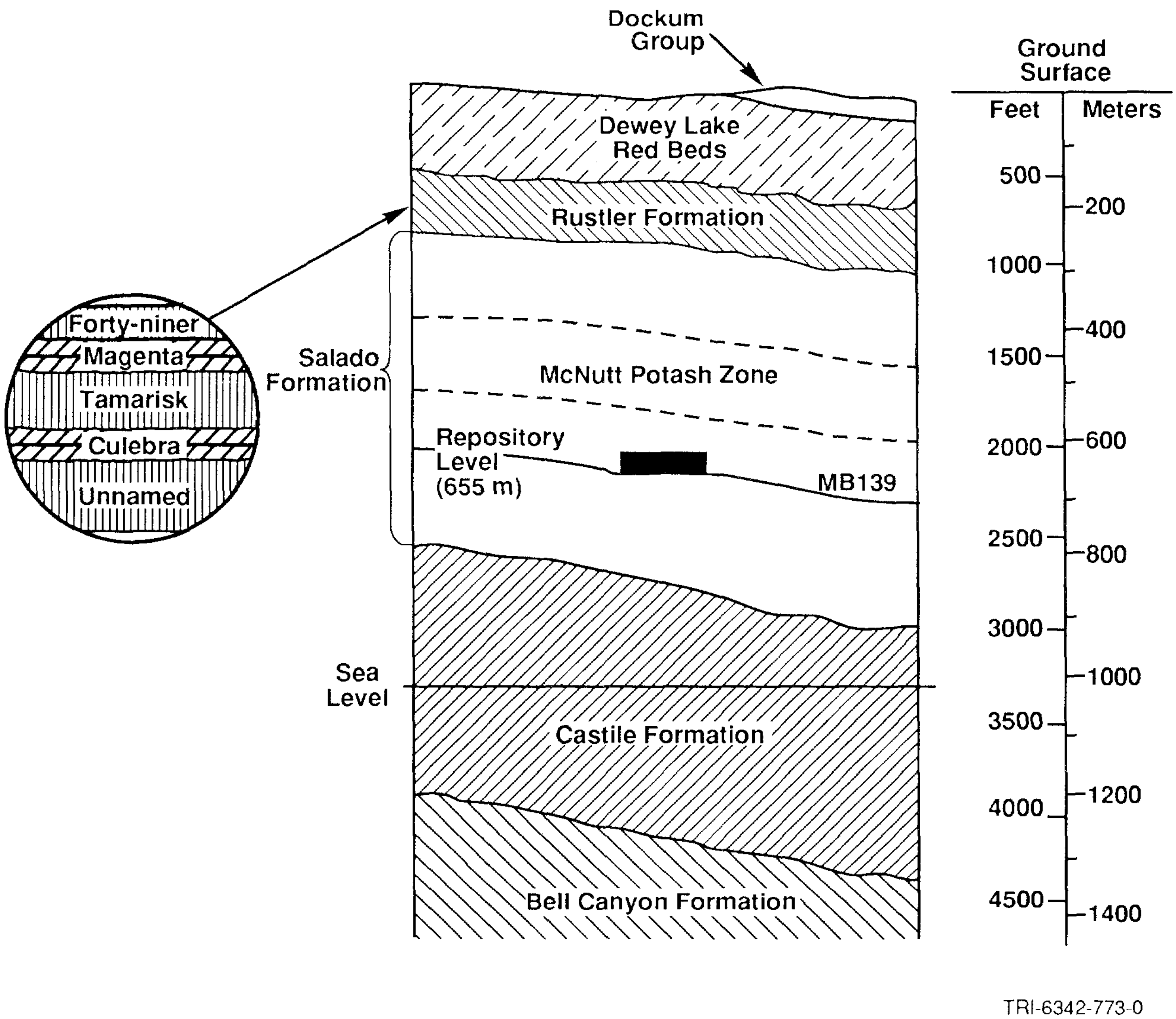

Figure 1-5. Generalized WIPP Stratigraphy (modified from Lappin, 1988).

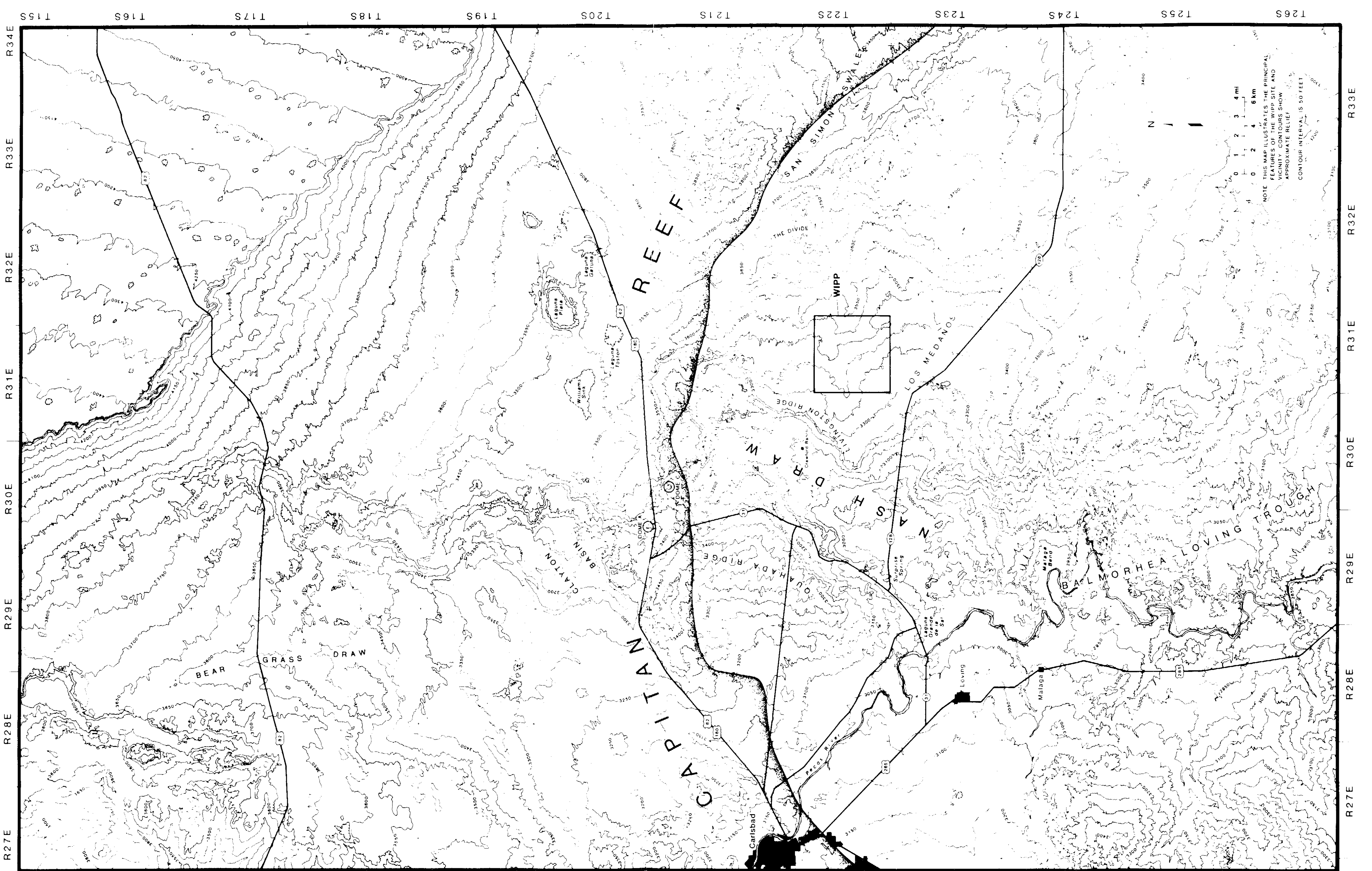

Figure 1-6. Topographic Map of the WIPP Area
(Bertram-Howery et al., 1990).

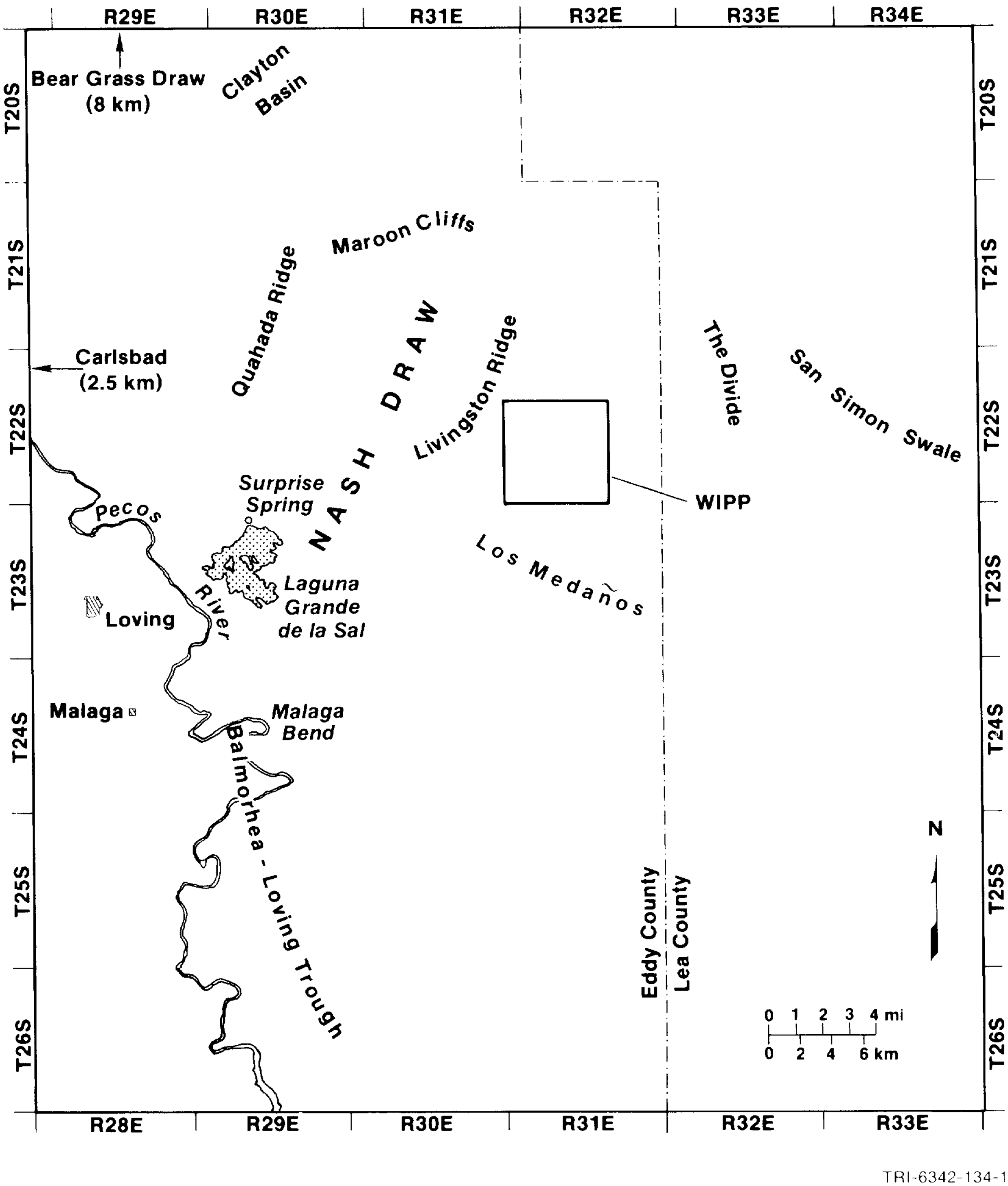

Figure 1-7. Map of the WIPP Area, Showing Physiographic Features (Bertram-Howery et al., 1990).

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, geologic depression, extends from just north of Carlsbad, New Mexico, into Texas west of Fort Stockton (Figure 1-8). 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 is contained in Powers et al. (1978a,b); Cheeseman (1978); Williamson (1978); Hiss (1975); Hills (1984); Harms and Williamson (1988); and Ward et al. (1986). A broad, low depression formed about 450 to 500 million years ago 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 System through the Quaternary System are shown in Table 1-1. During the Early and mid-Permian, the Delaware Basin subsided more rapidly, and a sequence of clastic rocks rimmed by reef limestone formed. The thickest of the reef deposits, the Capitan Limestone, is buried north and east of the WIPP but is exposed at the surface in the Guadalupe Mountains to the west (Figure 1-8). Evaporite deposits of the Castile Formation and the Salado Formation, which hosts the WIPP, filled the basin during the Late Permian 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.

Beginning with the Triassic Period and continuing to the present, the geologic record for the area is marked by long periods of nondeposition and erosion. Those formations that are present are either relatively thin or discontinuous and are not included in the performance assessment of the WIPP. Near the repository, the older, Permian-Period deposits below the Dewey Lake Red Beds were not affected by erosional processes during the past 250 million years (Lappin, 1988).

Minimal tectonic activity has occurred in the region since the Permian Period (Hayes, 1964; Williamson, 1978; Hills, 1984; Section 5.1.1-Regional Geology in Chapter 5 of this volume). 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-

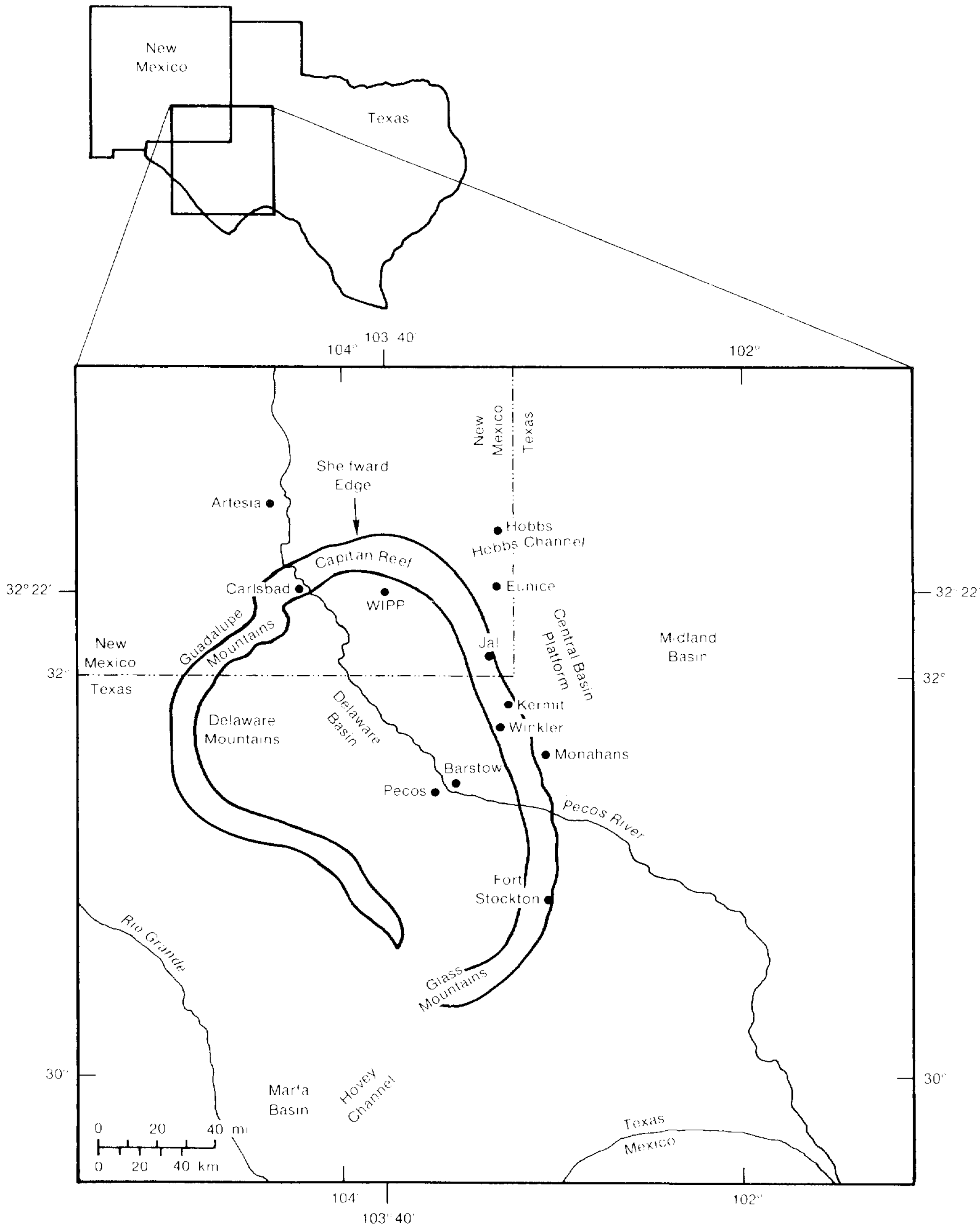

Figure 1-8. Location of the WIPP in the Delaware Basin (modified from Richey et al., 1985).

TABLE 1-1. MAJOR STRATIGRAPHIC DIVISIONS, SOUTHEASTERN NEW MEXICO

Erathem	System	Series	Formation	Age Estimate (yr)
Cenozoic	Quaternary	Holocene	Windblown sand	
		Pleistocene	Mescalero caliche	~500,000
			Gatuña Formation	~600,000±
	Tertiary	Pliocene, Miocene	Ogallala Formation	5.5 million
				24 million
		Oligocene, Eocene, Paleocene	Absent Southeastern New Mexico	
				66 million
Mesozoic	Cretaceous	Upper (Late)	Absent Southeastern New Mexico	
		Lower (Early)	Detritus preserved	
				144 million
	Jurassic		Absent Southeastern New Mexico	
				208 million
	Triassic	Upper (Late)	Dockum Group	
		Lower (Early)	Absent Southeastern New Mexico	
				245 million
Paleozoic	Permian, Upper (Late)	Ochoan	Dewey Lake Red Beds, Rustler Formation, Salado Formation, Castile Formation	
		Guadalupian	Capitan Limestone and Bell Canyon Formation	
	Permian, Lower (Early)	Leonardian	Bone Springs	
		Wolfcampian	Wolfcamp	
				286 million

Source: Modified from Bachman, 1987

Tertiary Period about 35 million years ago and is evidenced by a dike 16 km (10 mi) northwest of the WIPP (Powers et al., 1978a,b). Major volcanic activity last occurred over 1 billion years ago during Precambrian time (Powers et al., 1978a,b). None of these processes affected the Salado Formation at the WIPP.

Stratigraphy and Geohydrology

The Bell Canyon Formation of the Delaware Mountain Group is the deepest hydrostratigraphic unit being considered in the performance assessment

(Figure 1-5). Understanding fluid flow in the Bell Canyon is necessary because oil and gas drilling into deeper Pennsylvanian strata could penetrate the WIPP and saturated sandstones of the Bell Canyon Formation.

The Castile Formation near the WIPP consists of anhydrite and lesser amounts of halite. The Castile Formation is of interest because it contains discontinuous reservoirs of pressurized brine that could affect repository performance if penetrated by an exploratory borehole. Except where brine reservoirs are present, permeability of the Castile Formation is extremely low, and rates of groundwater flow are too low to affect the disposal system within the next 10,000 years.

The 250-million-year-old 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).

These lithologic layers are nearly horizontal at the WIPP, with a regional dip of less than one degree. The Salado Formation is intact in the WIPP area, and groundwater flow within it is extremely slow because primary porosity and open fractures are lacking in the highly plastic salt (Mercer, 1983). The formation may be saturated throughout the WIPP area, but low effective porosity allows for very little groundwater movement. The Salado Formation is discussed in more detail in Section 5.1.2-Stratigraphy in Chapter 5 of this volume.

The Rustler-Salado contact residuum, a transmissive, saturated zone of dissolution residue, occurs above the halite of the Salado Formation in and near Nash Draw. Brine in the Rustler-Salado contact residuum becomes more concentrated as it moves toward the southwest and is nearly saturated with salt in the lower region of Nash Draw near the Pecos River.

The Rustler Formation, the youngest unit of the Late Permian evaporite sequence, includes 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.

Most groundwater flow in the Rustler Formation occurs in 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 near the WIPP is apparently north to south (see "Potentiometric Surfaces" in Section 5.1.8-Confined Hydrostratigraphic Units in Chapter 5 of this volume). 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). Discharge is to the west-southwest either into the Pecos River at Malaga Bend (Hale et al., 1954; Hale and Clebsch, 1958; Havens and Wilkens, 1979; Mercer, 1983), into Cenozoic alluvium in the Balmorhea-Loving Trough, which is a series of coalesced, lens-shaped solution troughs formed by an ancestral Pecos River, or into both (Brinster, 1991). Culebra Dolomite Member water contains large concentrations of total dissolved solids (Haug et al., 1987; LaVenue et al., 1988).

Small amounts of water can be produced from the Magenta Dolomite Member from a thin, silty dolomite, along bedding planes of rock units, and along fractures (Mercer, 1983). The unit is present at and near the WIPP but is absent because of erosion in the southern part of Nash Draw. Regionally, flow direction is similar to flow in the Culebra Dolomite Member and is either toward Malaga Bend or more directly southward to the Balmorhea-Loving

Trough. Near the WIPP, flow is locally from east to west, perpendicular to flow in the Culebra.

Rock units younger than the Rustler Formation are believed to be unsaturated throughout most of the WIPP area. However, saturation of these units could occur as a result of climatic changes or breaching 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, 1987a). Three wells in the WIPP area produce only small amounts of water from the Dewey Lake Red Beds for livestock (Cooper and Glanzman, 1971).

The Dewey Lake Red Beds are unconformably overlain east of the WIPP by Triassic rocks of the undifferentiated Dockum Group (Figure 1-7). The lower Dockum is composed of poorly sorted, angular, coarse-grained to conglomeratic, thickly bedded material interfingering with shales. The 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 Clebsch, 1961; Richey et al., 1985). Recharge to the Triassic rocks is mainly from downward flow from overlying alluvium.

A long depositional hiatus occurred from Triassic time to the late Tertiary Period (Table 1-1). No rocks represent the Jurassic or Cretaceous Periods east of the Pecos River near the WIPP. 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 discontinuous stream deposits in channels and depressions (Bachman, 1980, 1984; Mercer, 1983); the informally named Mescalero caliche; and localized accumulations of alluvium and dune sands.

1.4.4 REPOSITORY/SHAFT SYSTEM

The WIPP repository is about 655 m (2,150 ft) below the land surface in the bedded salt of the Salado Formation. Present plans call for mining eight panels of seven rooms (Figure 1-9). 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, comprising two additional panel volumes, 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 (U.S. DOE, 1990b). Additional information on the repository design is in Chapter 5 of this volume.

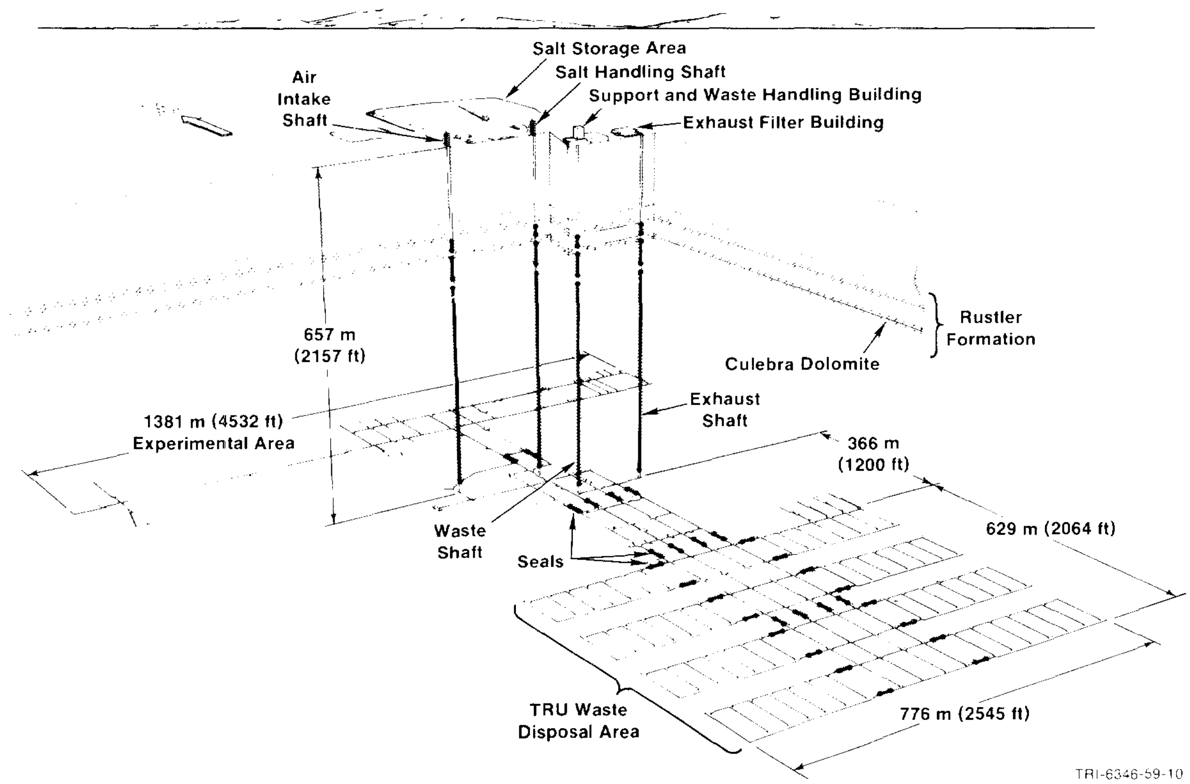

Figure 1-9. Proposed WIPP Repository, Showing Both TRU-Waste Disposal Areas and Experimental Areas (after Waste Management Technology Dept., 1987).

1.4.5 WASTE

The TRU waste for which WIPP is designed is defense-program waste generated by United States government activities since 1970. The waste consists of laboratory and production trash such as glassware, metal pipes, solvents, disposable laboratory clothing, cleaning rags, and solidified sludges. Along with other contaminants, the trash is contaminated by alpha-emitting transuranic (TRU) elements with atomic numbers greater than 92 (uranium), half-lives greater than 20 years, and curie contents greater than 100 nCi/g. Additional contaminants include other radionuclides of uranium and several contaminants with half-lives less than 20 years. Approximately 60 percent of the waste may be co-contaminated with waste considered hazardous under the Resource Conservation and Recovery Act (RCRA). The waste scheduled for disposal at the WIPP is described in more detail in Volume 3 of this report.

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) determine which TRU wastes will be accepted for emplacement at the WIPP. The most recent draft of the WAC report is currently being prepared (WIPP-DOE-69-Rev. 4), and much of the WAC data used in this report are from the Revision 4 draft. Data used in this report from the draft WAC are not expected to change in the published version. 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. Inventories of the waste to be disposed of at the WIPP are in Volume 3, Chapter 3 of this report.

Waste Form

Alpha-emitting TRU waste, although dangerous if inhaled or ingested, is not hazardous externally and can be safely handled if confined in a sealed container. Most of the waste, therefore, 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. The only containers that can currently be shipped to the WIPP in a TRUPACT-II (NuPac, 1989) truck-transport container are 55-gallon steel drums, metal standard waste boxes (SWBs), 55-gallon drums packed in an SWB, and an experimental bin overpacked in an SWB (U.S. DOE, 1990c). Additional information on waste containers is in Volume 3, Chapter 3 of this report.

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 (U.S. DOE, 1990a).

The WIPP's current design capacity for all radionuclides is 6.2 x 10^6 ft^3 (approximately 175,000 m^3) containing about 16,000,000 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 a design volume inventory, estimated at about 532,500 drums and 33,500 boxes of CH-TRU waste. The wastes are classified as retrievably stored or newly generated (future generated). If approved, ten defense facilities eventually will ship TRU waste directly to the WIPP: Idaho National Engineering Laboratory, Rocky Flats Plant, Hanford Reservation, Savannah River Site, Los Alamos National Laboratory, Oak Ridge National Laboratory, Nevada Test Site, Argonne National Laboratory-East, Lawrence Livermore National Laboratory, and Mound Laboratory (U.S. DOE, 1990c). Additional information on inventory estimates is in Volume 3 of this report.

A hazardous constituent of CH-TRU waste is lead that is present as incidental shielding, glovebox parts, and linings of gloves and aprons (U.S. DOE, 1990b). Trace quantities of mercury, barium, chromium, and nickel have also been reported. A significant quantity of aluminum is also identified in CH-TRU waste. An estimate of the quantity of metals and combustibles is discussed in Volume 3 of this report. Sludges contain a solidifier (such as cement), absorbent materials, inorganic compounds, complexing agents, and organic compounds including oils, solvents, alcohols, emulsifiers, surfactants, and detergents. The WAC waste-form requirements designate that the waste material shall be immobilized if greater than 1% by weight is particulate material less than 10 microns in diameter or if greater than 15% by weight is particulate material less than 200 microns in diameter. Only residual liquids in well-drained containers in quantities less than approximately 1% of the container's volume are allowed. Radionuclides in pyrophoric form are limited to less than 1% by weight of the external container, and no explosives or compressed gases are allowed. A list of CH-TRU waste forms identified as also containing trace quantities of hazardous chemical constituents is in Volume 3, Chapter 3 of this report. These hazardous materials are not regulated under 40 CFR Part 191 but are regulated separately by the EPA and New Mexico under the Resource Conservation and Recovery Act (RCRA). Many of these chemicals, if present in significant quantities, could affect the ability of radionuclides to migrate out of the repository by influencing rates of degradation of the organics, microbial activity, and gas generation. The effects of these processes are being studied.

Radionuclide Inventory

The radionuclide composition of CH-TRU waste varies depending upon the facility and process that generated the waste. The existing RH-TRU waste contains a wide range of radionuclides. An estimate of the CH- and RH-TRU radionuclide inventories is in Volume 3 of this report.

The fissile material content in equivalent grams of plutonium-239 allowed by the WAC for CH-TRU waste is a maximum of 200 g for a 55-gallon drum and 5 g/ft^3 up to 350 g for boxes. An RH-TRU waste package shall not exceed 600 g.

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 for certain other radionuclides (Appendix A of this volume). Although the initial WIPP inventory contains little or none of some of the listed nuclides, they will be produced as a result of radioactive decay and must be accounted for in the compliance evaluation; moreover, for compliance with the Individual Protection Requirements, 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, 1990). The Engineered Alternatives Task Force (EATF), assembled by WEC, identified specific alternatives, ranked alternatives according to specific feasibility criteria, and recommended 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.

Chapter 1–Synopsis

Purpose of This Report

Before disposing of transuranic (TRU) radioactive waste at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy (DOE) must have a reasonable expectation that the WIPP will comply with pertinent regulations. This report considers the regulations promulgated by the Environmental Protection Agency (EPA) as 40 CFR Part 191 (the Standard).

Regulatory compliance will be determined by establishing a reasonable expectation that long-term performance of the WIPP disposal system will meet the requirements of the Standard.

This 1991 report contains the second preliminary assessment of predicted long-term performance of the WIPP but does not yet provide a definitive assessment of compliance.

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.

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.

A repromulgated Standard is not expected before 1993.

Subpart A

> applies to a disposal facility prior to decommissioning and contains the standards for management and storage of TRU wastes,
>
> 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 disposal facility after it is decommissioned and contains the standards for disposal of TRU wastes,
>
> sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal (Containment Requirements),

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 nonmandatory guidance for implementing Subpart B.

A "Reasonable Expectation" of Compliance

Because of the uncertainties in long-term projections, the EPA does not expect absolute proof of the future performance of the disposal system.

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

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

Application of Additional Regulations to the WIPP

Resource Conservation and Recovery Act (RCRA)

The EPA has issued a conditional "no migration" determination for the WIPP Test Phase. The EPA determined that the DOE had demonstrated, to a reasonable degree of certainty, that hazardous constituents will not migrate from the disposal unit during the Test Phase.

National Environmental Policy Act (NEPA)

The DOE has issued environmental impact statements (EIS) evaluating the effects that disposal of radioactive wastes at the WIPP would have on the quality of the environment.

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 to assess whether 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 permenent disposal facility. The DOE will apply Subpart A of the Standard to the WIPP beginning with the first receipt of radionuclides for the Test Phase.

Participants in the WIPP Project

The DOE has overall responsibility for implementing the WIPP Project.

Westinghouse Electric Corporation (WEC) is the management and operating contractor (MOC) during the Test Phase. The MOC is responsible for operations once the decision is made to permanently emplace waste at the WIPP.

Sandia National Laboratories (SNL) provides 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.

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

The U.S. Congress assigned the Environmental Evaluation Group (EEG) the responsibility of independent technical evaluation of the WIPP.

Physical Setting

The WIPP is in southeastern New Mexico, about 42 km (26 mi) east of Carlsbad, the nearest major population center (pop. 25,000).

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 well water has always been poor; drinking water for the WIPP is supplied by pipeline.

Potash, oil, and gas are the only known important mineral resources in the area. Subject to valid existing rights, resource extraction is not allowed within the proposed land-withdrawal boundaries.

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

Minimal tectonic activity has occurred in the region during the past 250 million years. Faulting about 3.5 to 1 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 at the WIPP.

The Bell Canyon Formation, deposited more than 250 million years ago, is about 600 m (2,000 ft) below the WIPP repository. 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 discontinuous reservoirs of pressurized brine that could affect repository performance if breached by an exploratory borehole.

The Salado Formation, the bedded salt that hosts the WIPP, has slow 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.
>
> Groundwater flow in the Rustler Formation, above the residuum, is most rapid in the Culebra and Magenta Dolomite Members. Water in the Culebra Dolomite contains high concentrations of total dissolved solids; recharge is apparently an uncertain distance north of the WIPP, and discharge is to the west-southwest.

Units younger than the Rustler Formation are currently unsaturated throughout most of the WIPP area. However, climatic changes or breaching a pressurized reservoir could cause saturation in the future.

The WIPP Repository/Shaft System

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

Groundwater movement in the bedded salt is extremely slow; the repository has remained dry while it is ventilated, but slow seepage of brine 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.

Radionuclides Accepted at the WIPP

The TRU waste for which the WIPP is designed is defense-program waste generated by U.S. government activities since 1970.

A projected inventory shows that the contaminated waste will typically be composed of laboratory and production trash, including glassware, metal pipes, solvents, disposable laboratory clothing, cleaning rags, and solidified sludges.

Approximately 60 percent of the waste may be co-contaminated with waste considered hazardous under the Resource Conservation and Recovery Act (RCRA).

Most of the waste has external dose rates so low that people can handle properly sealed drums and boxes without any special shielding.

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.

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

2. APPLICATION OF SUBPART B TO THE WIPP

[NOTE: The text of Chapter 2 is followed by a synopsis that summarizes essential information, beginning on page 2-16.]

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 in this chapter. The full text of the Standard is reproduced as Appendix A of this volume.

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). The DOE compliance approach to the Standard is described in the WIPP *Compliance Strategy* (U.S. DOE, 1989a; also see U.S. DOE, 1990b).

The WIPP compliance assessment for Subpart B is based on four concepts. 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 combination of events and processes (scenario) is composed of phenomena that could occur at the WIPP. Similarly, evaluating the likelihood of events happening determines probabilities for 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 impacts and magnitudes of these uncertainties must be characterized and displayed. Thus, uncertainty analysis and sensitivity analysis are important parts of a performance assessment. Uncertainty analysis characterizes the uncertainty in analysis results that derive 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 results of detailed analyses. 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 the WIPP as a waste repository are not possible.

The EPA requirements for radionuclide containment and individual radiation protection drive the performance assessment. Chapter 2 documents the assumptions and interpretations of the Standard used in the performance assessment.

2.1 Containment Requirements

The primary objective of Subpart B is to isolate most of the waste from the accessible environment by limiting probabilities of long-term releases (U.S. EPA, 1985, p. 38070). This objective is reflected in § 191.13, the Containment Requirements.

2.1.1 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 undisturbed performance for the Individual Protection Requirements. 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, the 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 the engineered and 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 geologic and hydrologic features within the controlled area that inhibit release and migration of hazardous materials. 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).

2.1.2 HUMAN INTRUSION

In the Second Modification to the Consultation and Cooperation Agreement, the DOE agreed to prohibit further subsurface mining, drilling, slant drilling under the withdrawal 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 may 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).

Determining compliance with the Standard requires performance assessments that include the probabilities and consequences of disruptive events. The most significant event to affect a disposal system within a salt formation will probably be human intrusion. The EPA noted 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. 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 "taken into account" 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).

Three assumptions relative to human intrusion have been made by the WIPP performance-assessment team:

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 (§ 191.14(a)). The performance assessment will assume active control for the first 100 years.

While passive institutional controls are effective, no advertent 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.

The number of exploratory boreholes assumed to be drilled inside the controlled area through inadvertent human intrusion is to be based on site-specific information and, as specified in Appendix B of the Standard (U.S. EPA, 1985, p. 38089), 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 quantitatively 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 requires expert judgment. All approaches to assessing drilling probability presently being considered by SNL will include expert judgment.

2.1.3 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 by determining the waste unit factor, which is the inventory (in curies) of transuranic alpha-emitting radionuclides in the waste with half-lives greater than 20 years divided by one million curies, where transuranic is defined as radionuclides with atomic weights <u>greater</u> than 92 (uranium). Consequently, as currently defined in the Standard, all transuranic radioactivity in the waste cannot be included when calculating the waste unit factor. For the WIPP, 1.186 x 10^7 curies of the radioactivity design total of 1.814 x 10^7 curies comes from transuranic alpha-emitting radionuclides with half-lives greater than 20 years. This number is based on the design radionuclide inventories by waste generator for contact-handled (CH) and remotely handled (RH) waste (Volume 3, Chapter 3 of this report). Regardless of the waste unit, WIPP calculations have assumed that all nuclides in the design radionuclide inventories for CH- and RH-waste are regulated and must be included in the release calculations. Therefore, the release limits used by the WIPP are somewhat reduced and are more restrictive.

Note 6 of Table 1 in the Standard's Appendix A 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 the 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 (§ 191.13(a)). Potential releases estimated to have probabilities less than 0.001 are not limited (§ 191.13(a)). Calculation methods for summed normalized releases are described in more detail in Volume 3, Chapter 3 of this report.

2.1.4 UNCERTAINTIES

The EPA recognized that "[s]tandards must be implemented in the design phase for these disposal systems because active surveillance cannot be relied upon ..." over the very long time of interest. The EPA also recognized that "standards 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 (Chapter 3 of this volume; 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, uncertainties in the conceptual model and its mathematical representation, and scenario uncertainty. The WIPP Project will use expert judgment for parameters or models identified by sensitivity analyses as being important to WIPP performance assessment and for which significant uncertainty exists in the data sets and conceptual models. Thus far, conditional on existing data sets and conceptual models, these parameters include radionuclide solubility, geochemical retardation of radionuclides in the Culebra Dolomite above the repository, dual porosity, permeabilities related to the repository room and its contents, and human-intrusion borehole properties. Data from expert panels quantifying radionuclide concentrations in brines in WIPP waste panels and radionuclide retardation in the Culebra Dolomite are being compiled.

Additional expert panels are planned to quantify other parameters and thus address the uncertainty in using those important data sets and associated conceptual models.

In addition, WIPP performance assessment must also include the potential for human intrusion and the effectiveness of passive institutional controls to deter such intrusion. Including these factors in the WIPP performance assessment requires using expert judgment. An expert panel has already identified future societies' possible technical capabilities, needs, and levels of intelligence. An additional panel is currently developing a marker methodology to maximize both information that could be communicated to future generations and marker lifetimes. Another expert panel may develop strategies concerning barriers to intrusion-by-drilling.

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 (checked for correctness) to the extent possible, expert judgment will be relied upon where validation is not possible. Uncertainties arising from the numerical solutions of a 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, 1990b).

The WIPP Project will assess and reduce uncertainty to the extent practicable using a variety of techniques (Table 2-1). The techniques in Table 2-1 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 2-1 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 estimated behavior, performance, and 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.

TABLE 2-1. TECHNIQUES FOR ASSESSING OR 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 Uncertainty 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, 1989b

2.1.5 COMPLIANCE ASSESSMENT

The Standard assumes that the results of the performance assessment for § 191.13(a) will be incorporated into an overall probability distribution of cumulative release to the extent practicable. In Appendix B, the EPA assumes that, whenever practicable, results can be assembled into a single complementary cumulative distribution function (CCDF) that indicates the probability of exceeding various levels of summed normalized cumulative releases (Figure 2-1).

Descriptions of a 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 from the development of scenario probabilities and the calculation of scenario consequences. Further, the effects of different types of uncertainties can be shown by constructing families of CCDFs and then reducing each family to a

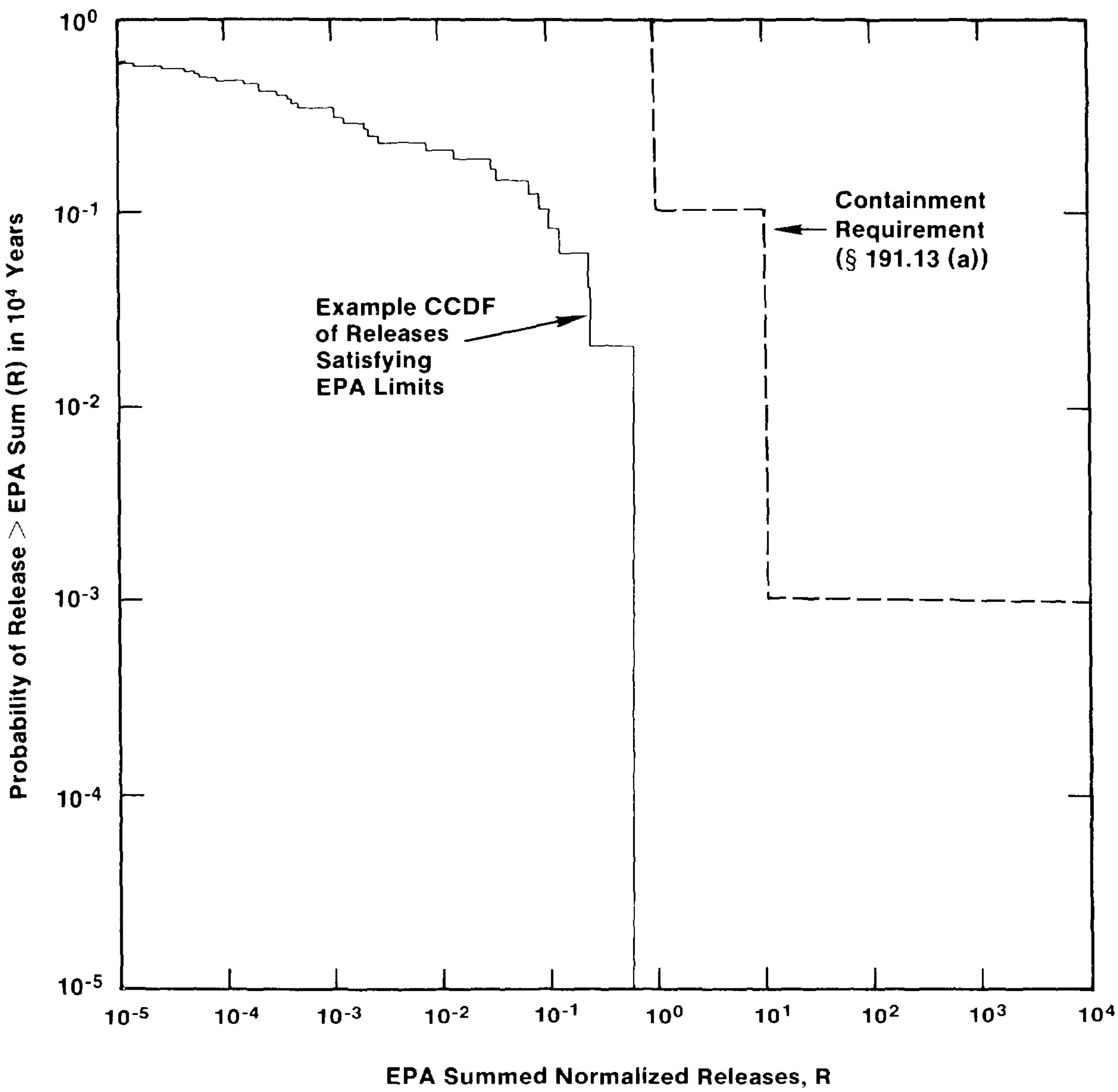

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Figure 2-1. Hypothetical CCDF Illustrating Compliance with the Containment Requirements (after Marietta et al., 1989).

single CCDF. The construction of families of CCDFs and the single CCDF is described in Chapter 3 of this volume.

The EPA assumes that a single CCDF will incorporate all 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 not mandatory. A basis for concluding that a system provides good isolation can include qualitative judgment as well as quantitative results and thus 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 guidance states that

> 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.... 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 (U.S. EPA, 1985, p. 38088).

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).

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 4 and 5 of this volume), all CCDF curves presented in Chapter 6 of this volume 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 (Volume 2 of this report) and incomplete data (Volume 3 of this report) and because the Standard has not been repromulgated.

2.1.6 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 had been performed for TRU wastes. The EPA evaluated the costs of the various engineering controls potentially needed for repositories for <u>commercially</u> generated spent fuel or high-level waste 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 prior to promulgation of the Standard for the only TRU-defense-waste repository, the WIPP. An impact study was recently initiated for TRU-waste repositories, but findings are not yet available.

2.2 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 demonstrating 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 for the WIPP. A selected disposal system that permits possible future recovery of most 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, 1990b). In promulgating the Standard, the EPA stated that "[t]he intent of this provision was not to make recovery of waste easy or cheap, but merely possible...because the [EPA] believes that future generations should have options to correct any mistakes that this generation might unintentionally make" (U.S. EPA, 1985, p. 38082). The EPA also stated that "<u>any</u> current concept for a mined geologic repository meets this requirement <u>without</u> any additional procedures or design features" (ibid.).

2.3 Individual Protection Requirements

The Individual Protection Requirements (§ 191.15) of the Standard require predicting potential doses to humans resulting from releases to the accessible environment for undisturbed performance 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 estimate doses as specified by the Individual Protection Requirements. One of the products of scenario development for the Containment Requirements is a scenario for undisturbed conditions. The undisturbed performance of the repository is its design-basis behavior and reasonable variations in that behavior resulting from uncertainties in natural barriers and in designing systems and components to function for 10,000 years. 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, 1990b).

> "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 are 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 and potentially cause the release of radionuclides. Only the presence of groundwater has significantly affected the Salado near 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 (U.S. EPA, 1985, p. 38088).

The Individual Protection Requirements state that "the annual dose equivalent from the disposal system to any member of the public in the accessible environment" shall not exceed "25 millirems to the whole body or 75 millirems to any critical organ" (§ 191.15). These requirements apply to undisturbed performance of the disposal system, considering all potential release and dose pathways for 1,000 years after disposal. A specifically stated requirement is that modeled individuals be assumed to consume 2 ℓ (0.5 gal) per 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 at tested locations within the proposed land withdrawal area. At most well locations, water-bearing units meet neither requirement (i) nor (iii): total dissolved solids exceed 10,000 mg/ℓ and transmissivity is less than 200 gallons per day per foot (26.8 ft^2/day or 2.9 x 10^{-5} m^2/s) (Lappin et al., 1989; Brinster, 1991). Outside the land withdrawal area, however, portions of the Culebra Dolomite Member do meet the requirements of the first definition. The WIPP Project will assume that any portion of an aquifer that meets the first definition is a significant source of groundwater and will examine communication between nonqualifying and qualifying portions. 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. Based on current evaluations, neither the Magenta Dolomite Member nor the Culebra Dolomite Member of the Rustler Formation (Figure 1-5) appears to meet the entire definition of 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). Studies will include reviewing and assessing regional and WIPP drilling records and borehole histories for pertinent hydrologic information (U.S. DOE, 1990b).

No releases from the repository/shaft system are expected to occur within 1,000 years (Lappin et al., 1989; Marietta et al., 1989; Chapter 7 of this volume); therefore, dose predictions for undisturbed performance could be unnecessary. To date, analyses of undisturbed conditions suggest successful long-term isolation of the waste.

2.4 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 as defined in § 191.16 at the WIPP; therefore, the requirement to analyze radionuclide concentrations in such groundwater is not relevant to the WIPP (see Chapter 9 of this volume).

Chapter 2-Synopsis

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.

Containment Requirements

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

Performance Assessment

Subpart B of the Standard 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.

Disposal systems are to be designed to provide a reasonable expectation, based on performance assessments, that cumulative releases for 10,000 years after disposal from all significant processes and events that may affect the disposal system 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.

This report refers to the assessment of compliance with both the Containment Requirements and the Individual Protection Requirements as the "WIPP performance assessment."

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, such as post-operational monitoring, maintaining fences and buildings, and guarding the facility, 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.

Three assumptions relative to human intrusion at the WIPP have been made by the performance-assessment team:

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 are effective, no advertent 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.

No more than 30 exploratory boreholes/km^2 (0.4 mi^2) will be assumed drilled inside the controlled area through inadvertent human intrusion 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 factor" that considers alpha-emitting radionuclides with atomic weights greater than 92 (uranium) with half-lives <u>greater</u> than 20 years. Consequently, all TRU waste scheduled for disposal in the WIPP cannot be included when calculating the waste-unit factor.

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 the requirements.

Uncertainties

For the WIPP, uncertainties in parameters, scenarios, and mathematical, conceptual, and computer models are significant considerations.

The WIPP Project will reduce uncertainty to the extent practicable using a variety of techniques that are typically applied iteratively.

Expert judgment will be used for parameters that have significant uncertainty in data sets.

Expert judgment will also be used to include the potential for human intrusion and the effectiveness of passive institutional controls to deter such intrusion.

Models will be validated (checked for correctness) to the extent possible. Expert judgment must be relied upon where validation is not possible.

Compliance Assessment

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

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

According to the EPA guidance, 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; EPA guidance states that compliance should be determined from all information assembled by the DOE, including qualitative judgments.

The likelihood that excess releases will occur must be considered in a qualitative decision about a "reasonable expectation" of compliance but is not necessarily the deciding factor.

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.

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,

monitoring to mitigate against unexpectedly poor system performance going undetected,

using markers and records to reduce the chances of systematic and inadvertent intrusion,

including multiple barriers, both manmade 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,

selecting a disposal system that permits possible future recovery of most 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 humans 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 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.

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3. PERFORMANCE-ASSESSMENT OVERVIEW

Jon C. Helton[1]

[NOTE: The text of Chapter 3 is followed by a synopsis that summarizes essential information, beginning on page 3-85.]

The design and implementation of a performance assessment is greatly facilitated by a clear conceptual model for the performance assessment itself. The purpose of this chapter is to present such a model and then to indicate how the individual parts of the WIPP performance assessment fit into this model. The WIPP performance assessment is, in effect, a risk assessment. As a result, a conceptual model that has been used for risk assessments for nuclear power plants and other complex systems is also appropriate for the WIPP performance assessment.

3.1 Conceptual Model for WIPP Performance Assessment

3.1.1 RISK

Risk is often defined as consequence times probability or consequence times frequency. However, this definition 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 are the consequences of things going wrong. The latter description provides a structure on which both the representation and calculation of risk can be based.

In recognition of this, Kaplan and Garrick (1981) have proposed a representation for risk based on sets of ordered triples. Specifically, they propose that risk be represented by a set R of the form

$$R = \{(S_i, pS_i, \mathbf{cS}_i), i=1, \ldots, nS\}, \qquad (3\text{-}1)$$

where

S_i = a set of similar occurrences,

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

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$\mathbf{cS}_i$ = 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 the consequences for each 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 information associated with scenario S_i. The set R in Equation 3-1 will be used as the conceptual model for the WIPP performance assessment.

Although the representation in Equation 3-1 provides a natural 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 $\mathbf{cS}$ 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

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

$$= \sum_{j=i}^{nS} pS_j, \qquad (3\text{-}2)$$

where i is the smallest integer such that $cS_i > x$. As illustrated in Figure 3-1, 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 that is more suggestive of the information that it displays. To avoid a broken appearance, CCDFs are often plotted in the form shown in Figure 3-2, which is the same as Figure 3-1 except that vertical lines have been added at the discontinuities.

The steps in the CCDFs shown in Figure 3-1 and Figure 3-2 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 3-2 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

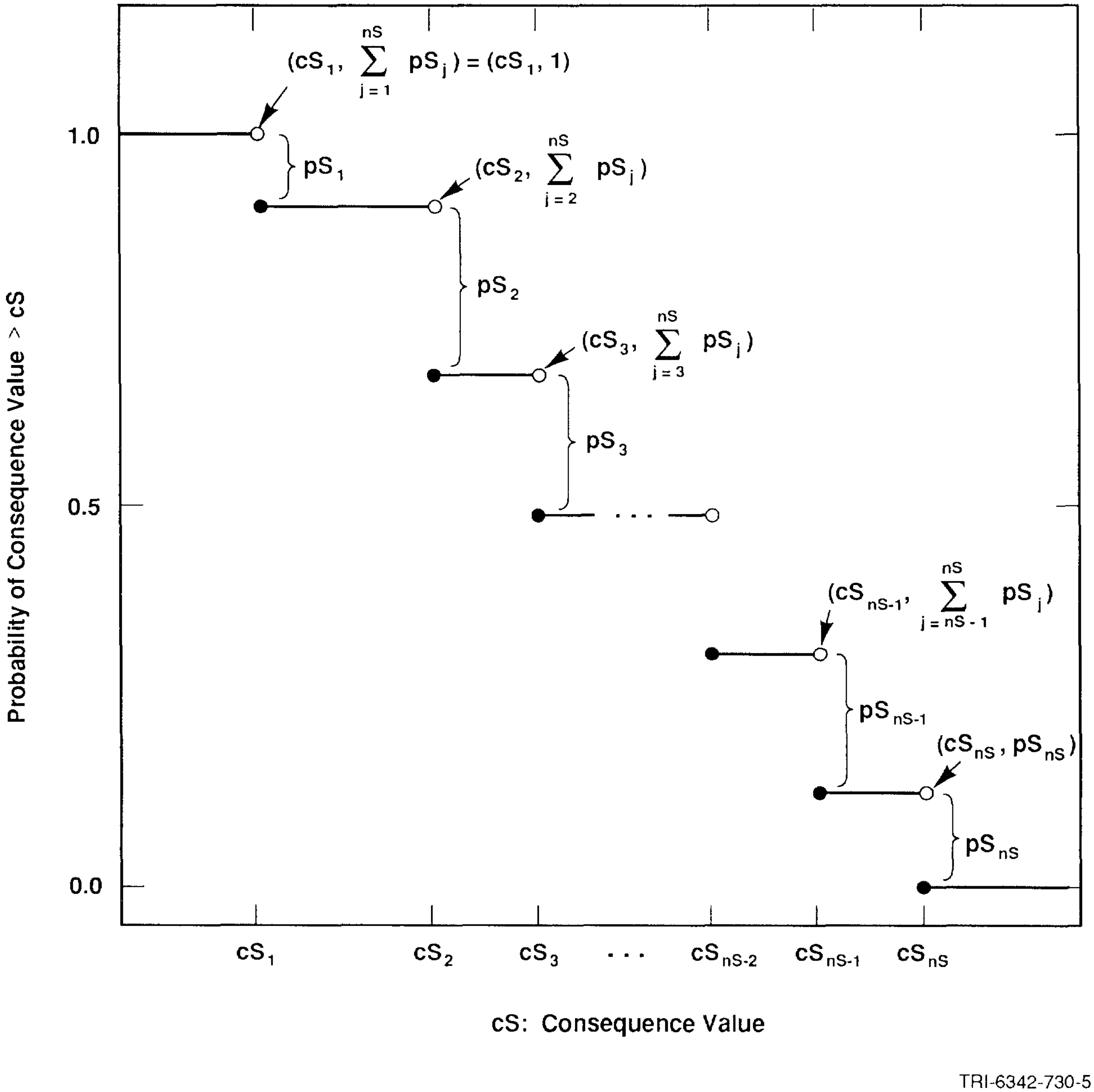

Figure 3-1. Estimated CCDF for Consequence Result cS (Helton et al., 1991). The open and solid circles at the discontinuities indicate the points included on (solid circles) and excluded from (open circles) the CCDF.

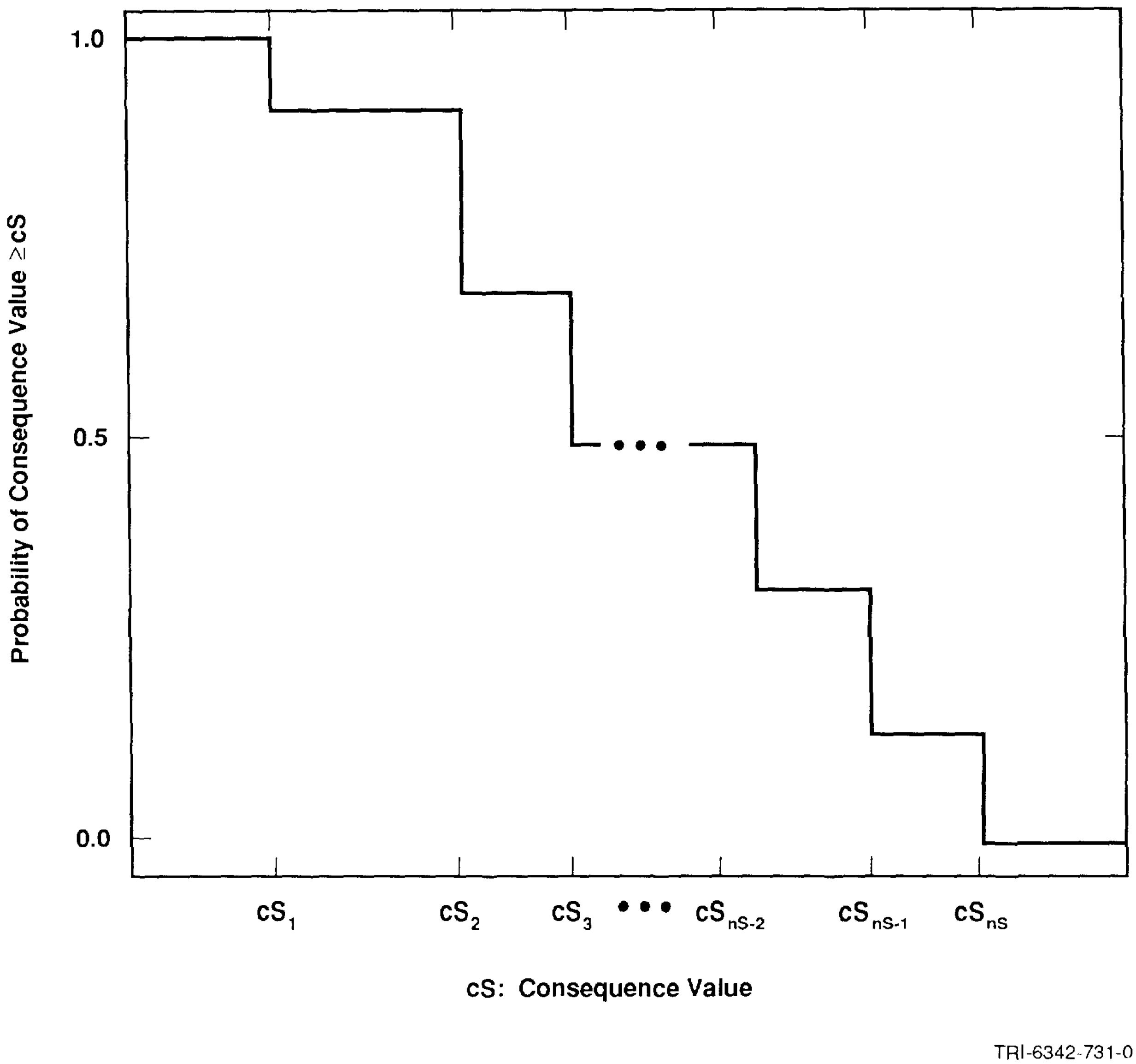

Figure 3-2. Estimated CCDF for Consequence Result cS Including Vertical Lines at the Discontinuities (Helton et al., 1991). This figure is the same as Figure 3-1 except for the addition of the vertical lines at the discontinuities.

available information and computational cost, will always limit how far such efforts can be carried. The consequence result of greatest interest in the WIPP performance assessment is the EPA sum of normalized radionuclide releases to the accessible environment. This sum is one of many predicted quantities (e.g., travel time, dose to humans, ...) that could be the variable on the abscissa in Figures 3-1 and 3-2. However, the normalized release is special in that the Standard places restrictions on certain points on its CCDF. As discussed in Chapter 2 and illustrated in Figure 3-3, the probabilities of exceeding 1 and 10 are required to be less than 0.1 and 0.001, respectively. The CCDF in Figure 3-3 is drawn as a smooth curve, which is the limiting case for a large number of scenarios S_i. If the number of scenarios S_i is small, then the CCDF for the normalized sum will resemble the step functions shown in Figures 3-1 and 3-2, although smoothing procedures can be used to develop continuous approximations to these curves. Additional discussion of the CCDF for normalized releases is given in Section 3.1.4-Risk and the EPA Limits.

3.1.2 UNCERTAINTY IN RISK

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 3-1 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 system under consideration. In terms of the risk representation in Equation 3-1, 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 cS_i. Similarly, once the models for use have been selected, imprecisely known variables required by these models can affect both pS_i and 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 Figures 3-1 and 3-2 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 Figures 3-1 and 3-2.

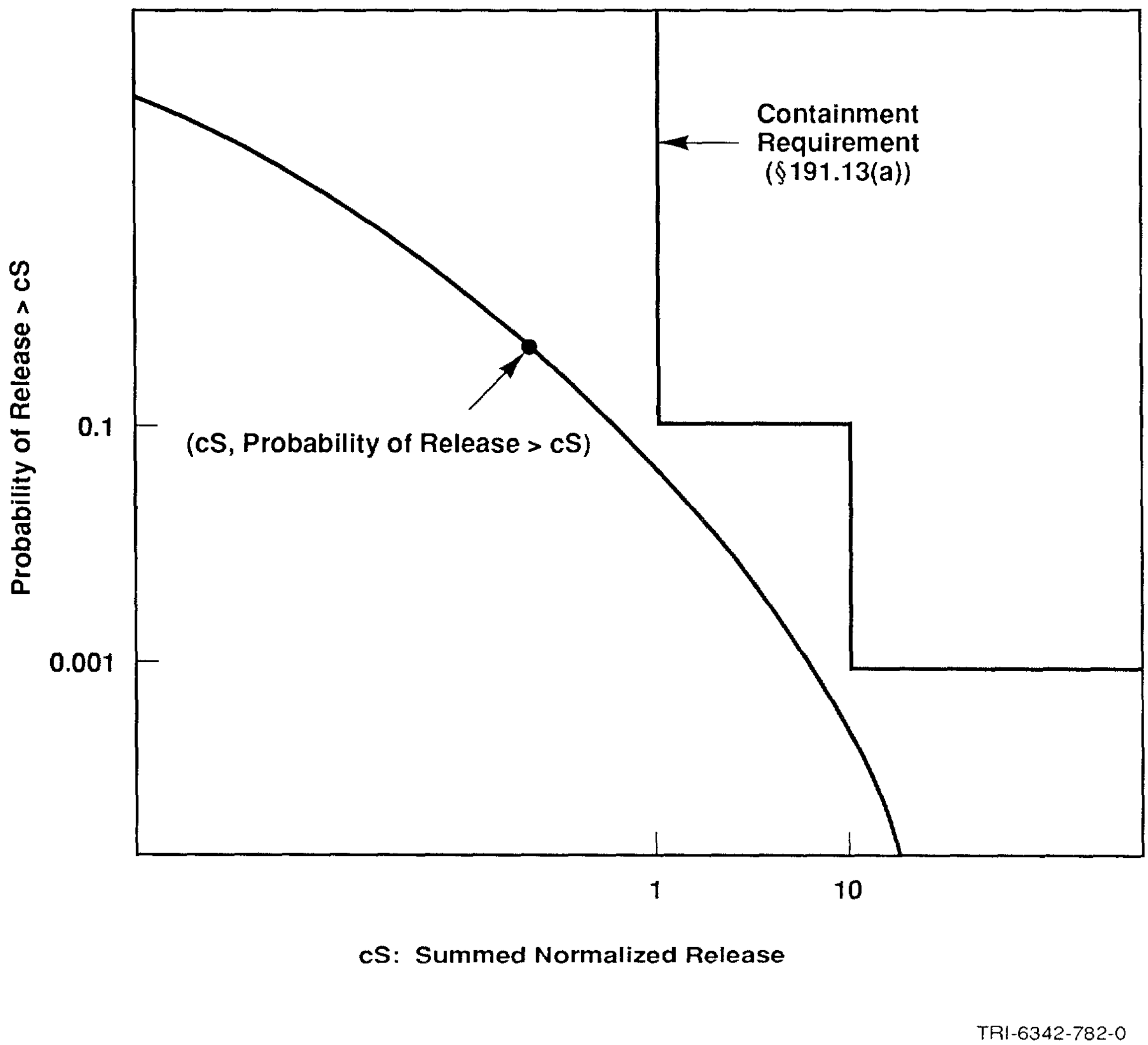

Figure 3-3. Illustration of Hypothetical CCDF for Summed Normalized Release for Containment Requirements (§ 191.13(a)). For a limited number of scenarios, the CCDF will look like the step functions shown in Figures 3-1 and 3-2.

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

These imprecisely known variables can be represented by a vector

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

where each x_j is an imprecisely known input required in the analysis and nV is the total number of such inputs. In concept, the individual x_j could be almost anything, including vectors or functions required by an analysis and indices pertaining to the use of several alternative models. However, an overall analysis, including uncertainty and sensitivity studies is more likely to be successful if the risk representation in Equation 3-1 has been developed so that each x_j is a real-valued quantity for which the overall analysis requires a single value, but it is not known with preciseness what this value should be. With the preceding ideas in mind, the representation for risk in Equation 3-1 can be restated as a function of $\mathbf{x}$:

$$R(\mathbf{x}) = \{(S_i(\mathbf{x}), pS_i(\mathbf{x}), \mathbf{cS}_i(\mathbf{x})), i=1, \ldots, nS(\mathbf{x})\}. \tag{3-4}$$

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 the vector $\mathbf{cS}$ shown in Equation 3-1, 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).

3.1.3 CHARACTERIZATION OF UNCERTAINTY IN RISK

If the inputs to a performance assessment as represented by the vector **x** in Equation 3-3 are uncertain, then so are the results of the assessment. Characterization of the uncertainty in the results of a performance assessment requires characterization of the uncertainty in **x**. Once the uncertainty in **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 **x** is a sequence of probability distributions

$$D_1, D_2, \ldots, D_{nV}, \tag{3-5}$$

where D_j is the distribution developed for the variable x_j, $j=1, 2, \ldots, nV$, contained in **x**. The definition of these distributions may also be accompanied by the specification of 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 performance 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 from available information through a suitable review process and serves to assemble information from many sources into a form appropriate for use in an integrated analysis. However, it is possible that the D_j may be obtained by classical statistical techniques for some variables.

Once the distributions in Equation 3-5 have been developed, Monte Carlo techniques can be used to determine the uncertainty in $R(\mathbf{x})$ from the uncertainty in **x**. First, a sample

$$\mathbf{x}_k = [x_{k1}, x_{k2}, \ldots, x_{k,nV}], \; k=1, \ldots, nK, \tag{3-6}$$

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

$$R(\mathbf{x}_k) = \{(S_i(\mathbf{x}_k), pS_i(\mathbf{x}_k), \mathbf{cS}_i(\mathbf{x}_k)), \; i=1, \ldots, nS(\mathbf{x}_k)\} \tag{3-7}$$

for k=1, ..., nK. Each set $R(\mathbf{x}_k)$ is the result of one complete performance assessment performed with a set of inputs (i.e., $\mathbf{x}_k$) that the review process producing the distributions in Equation 3-5 concluded was possible. Further, associated with each risk result $R(\mathbf{x}_k)$ in Equation 3-7 is a probability or weight[1] that can be used in making probabilistic statements about the distribution of $R(\mathbf{x})$.

In most performance assessments, CCDFs are the results of greatest interest. For a particular consequence result, a CCDF will be produced for each set $R(\mathbf{x}_k)$ of results shown in Equation 3-5. This yields a distribution of CCDFs of the form shown in Figure 3-4.

Although Figure 3-4 provides a complete summary of the distribution of CCDFs obtained for a particular consequence result by propagating the sample shown in Equation 3-6 through a performance assessment, the figure is hard to read. A less crowded summary can be obtained by plotting the mean value and selected percentile values of the exceedance probabilities shown on the ordinate 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.[1] The determination of the mean and percentile values for cS = 1 is illustrated in Figure 3-5. If the mean and percentile values associated with individual consequence values are connected, a summary plot of the form shown in Figure 3-6 is obtained. Due to their construction, the percentile curves hold pointwise above the abscissa, and thus, do not define percentile bounds for the distribution of $R(\mathbf{x})$, which is a distribution of functions. However, the mean curve is an estimate for the expected value of this distribution of functions.

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.

---

[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. This weight is often referred to as the probability for each observation (i.e., sample element $\mathbf{x}_k$). However, this is not technically correct. If continuous distributions are involved, the actual probability of each observation is zero.

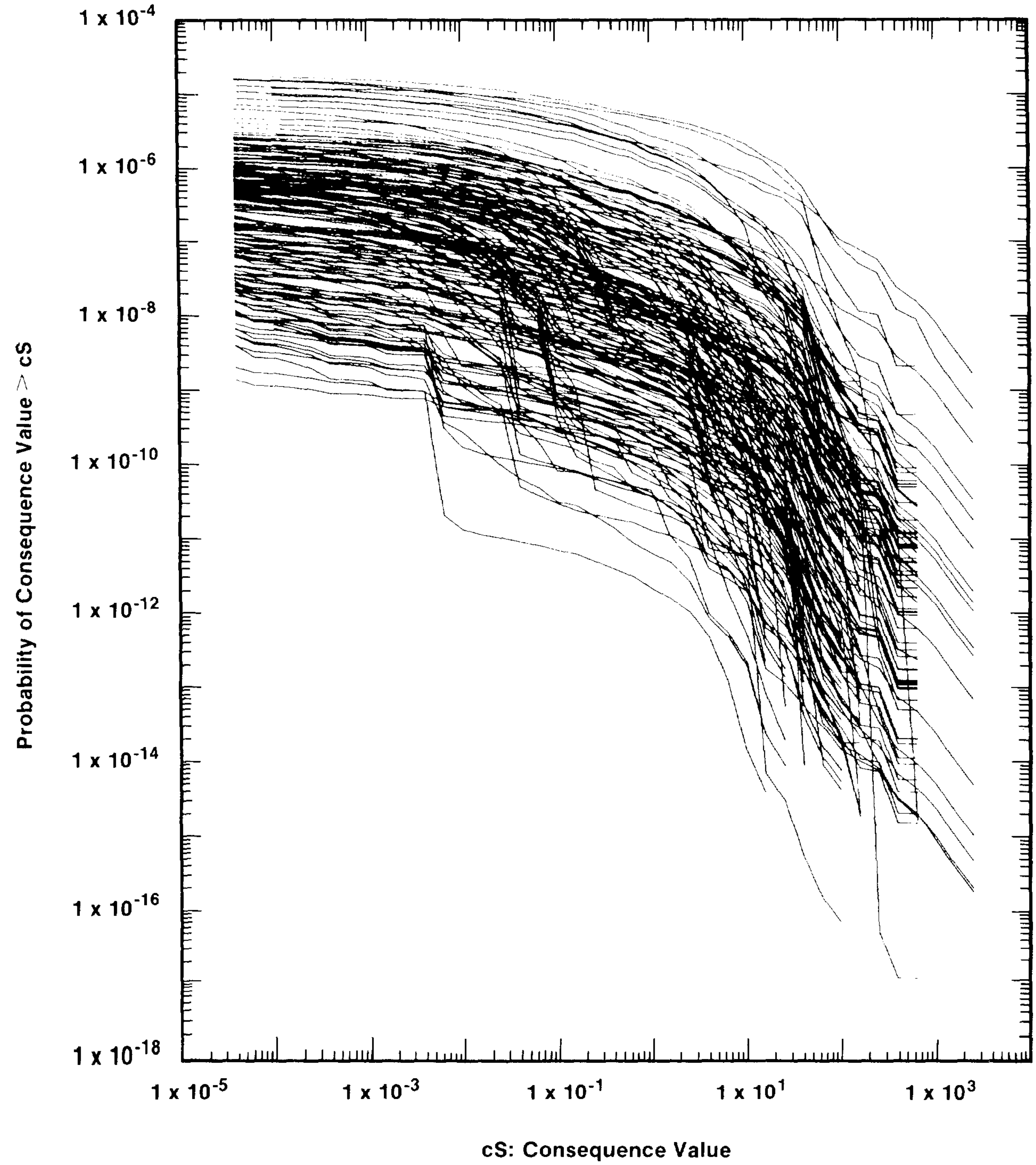

Figure 3-4. Example Distribution of CCDFs Obtained by Sampling Imprecisely Known Variables (after Breeding et al., 1990).

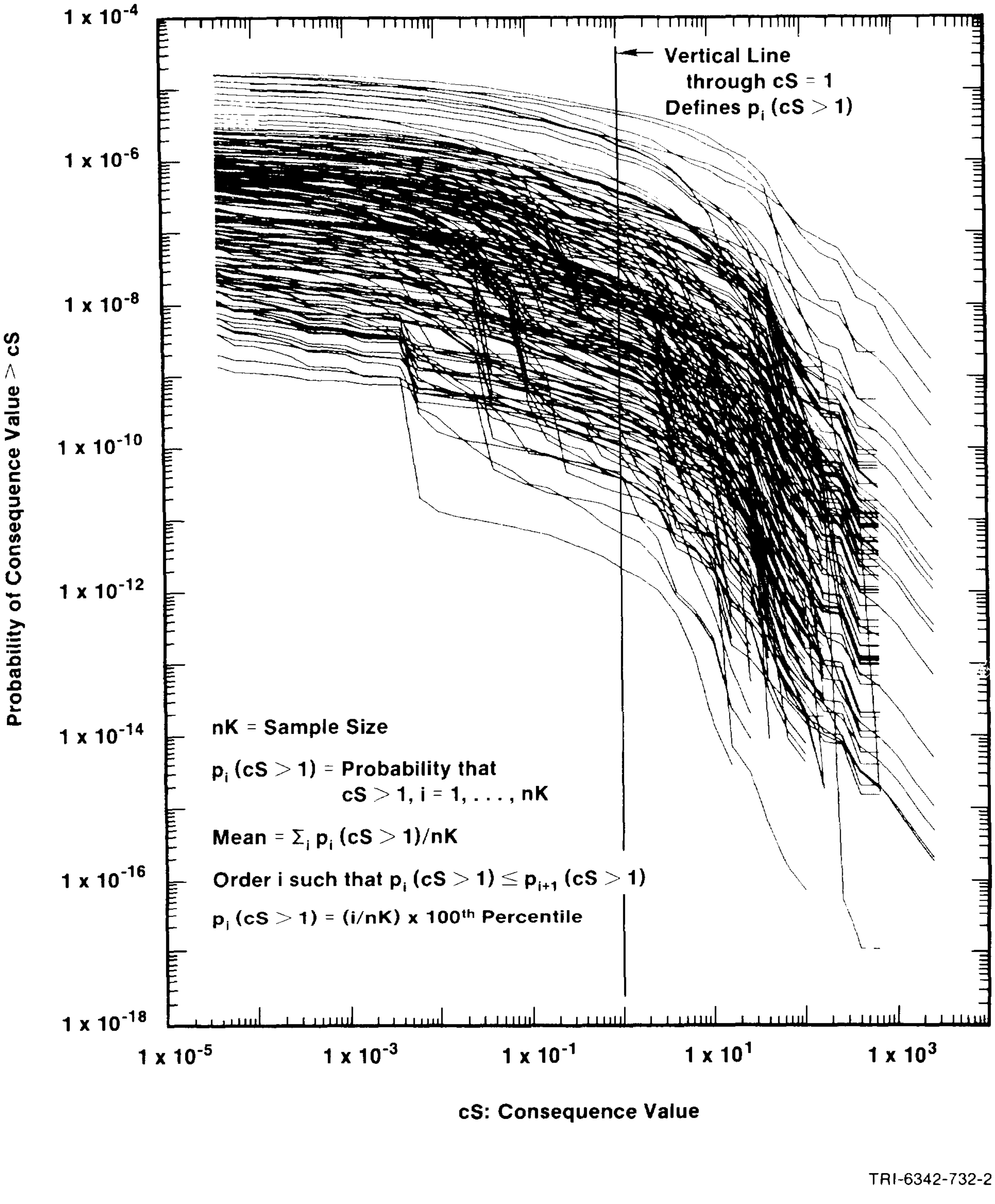

Figure 3-5. Example Determination of Mean and Percentile Values for cS = 1 in Figure 3-4.

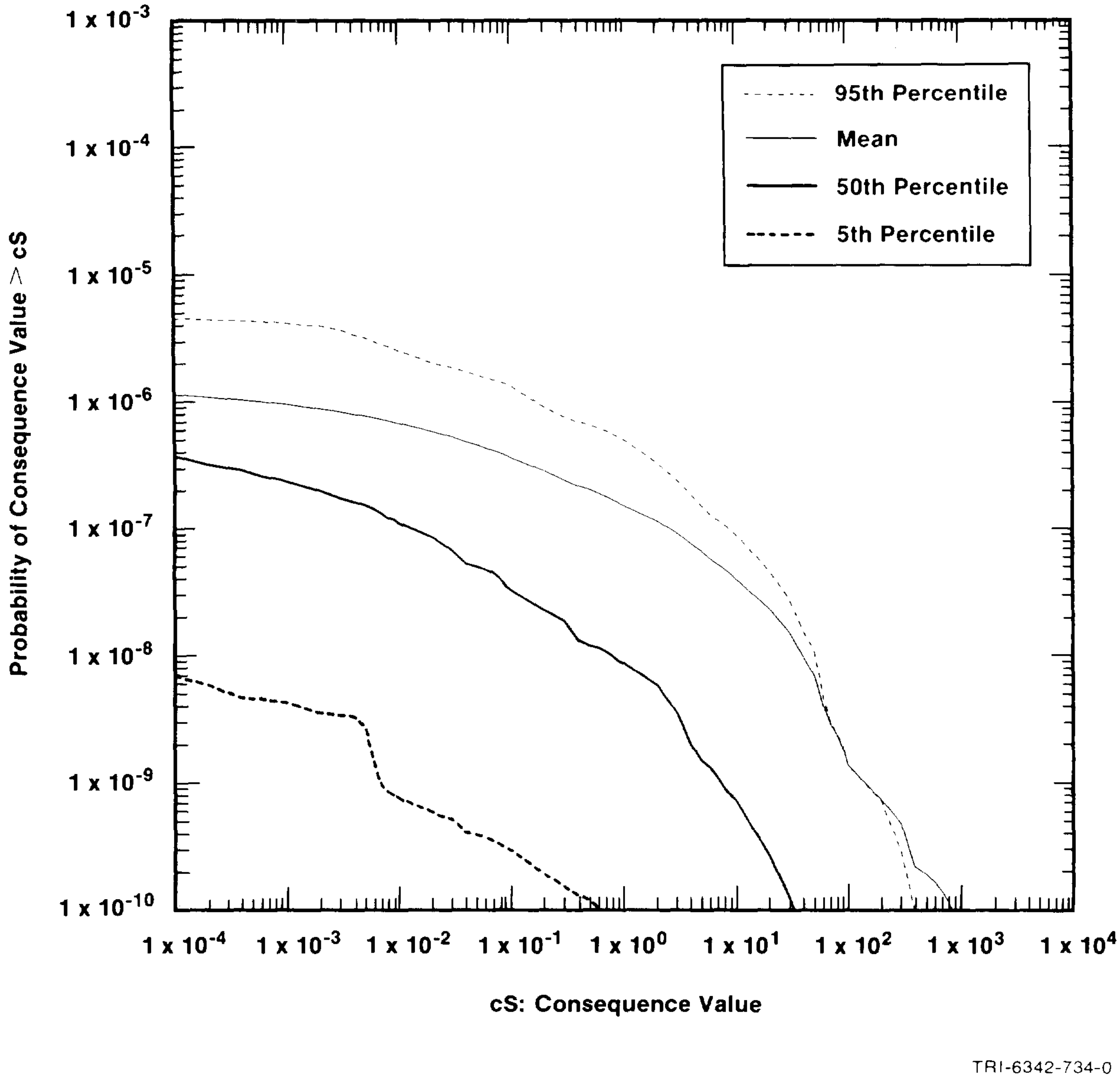

Figure 3-6. Example Summary Curves Derived from an Estimated Distribution of CCDFs (after Breeding et al., 1990). The curves in this figure were obtained by calculating the mean and the indicated percentiles for each consequence value on the abscissa in Figure 3-4 as shown in Figure 3-5. The 95th percentile curve crosses the mean curve due to the highly skewed distributions for exceedance probability. This skewness also results in the mean curve being above the median (i.e., 50th percentile) curve.

The answer to questions of the first type is provided by results of the form shown in Figure 3-4, 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 3-6 summarize the distribution in Figure 3-4. The percentile curves in Figure 3-6 also provide a way to place confidence limits on the risk results in Figure 3-4. For example, the probability is 0.9 that the exceedance probability for a specific consequence value 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 3-6. 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 3-6 are shown in Figure 3-7.

Uncertainty in risk results due to imprecisely known variables and uncertainty in estimates for means and other statistical summaries that result from imprecisely known variables can be displayed in a single plot as shown in Figure 3-8. 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 3-6. As indicated earlier, this produces confidence intervals that hold pointwise along the abscissa. Similarly, the mean curve would be obtained by averaging over the same curves that gave rise to the preceding confidence intervals. The confidence intervals for the mean would have to be derived by replicated sampling or some other appropriate statistical procedure.

The point of greatest confusion involving the risk representation in Equation 3-1 is probably the distinction between the uncertainty that gives rise to a single CCDF and the uncertainty that gives rise to a distribution

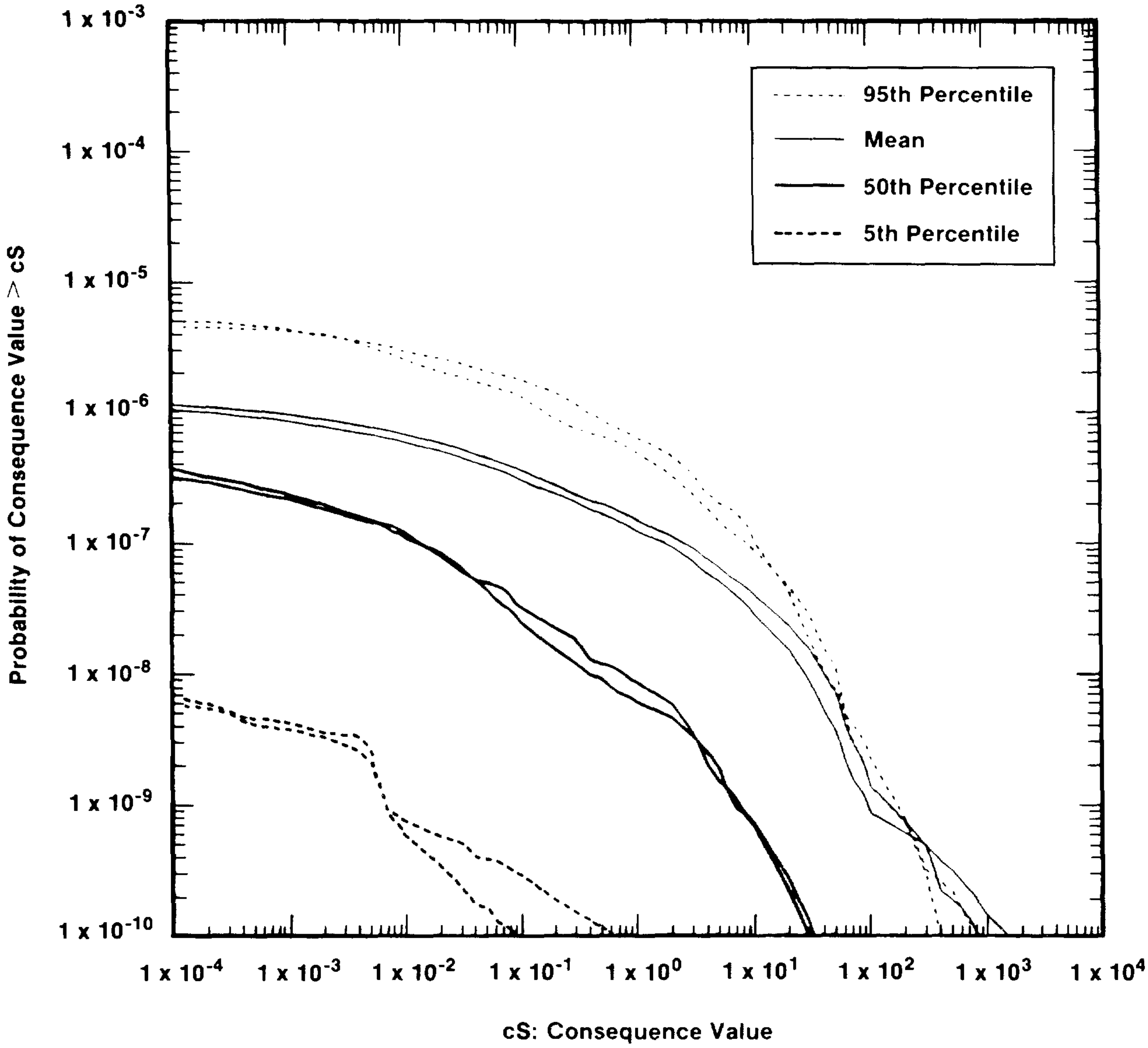

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Figure 3-7. Example of Mean and Percentile Curves Obtained with Two Independently Generated Samples for the Results Shown in Figure 3-4 (after Breeding et al., 1990; additional discussion is provided in Iman and Helton, 1991). The two samples have the same number of elements and differ only in the random seed used in their generation.

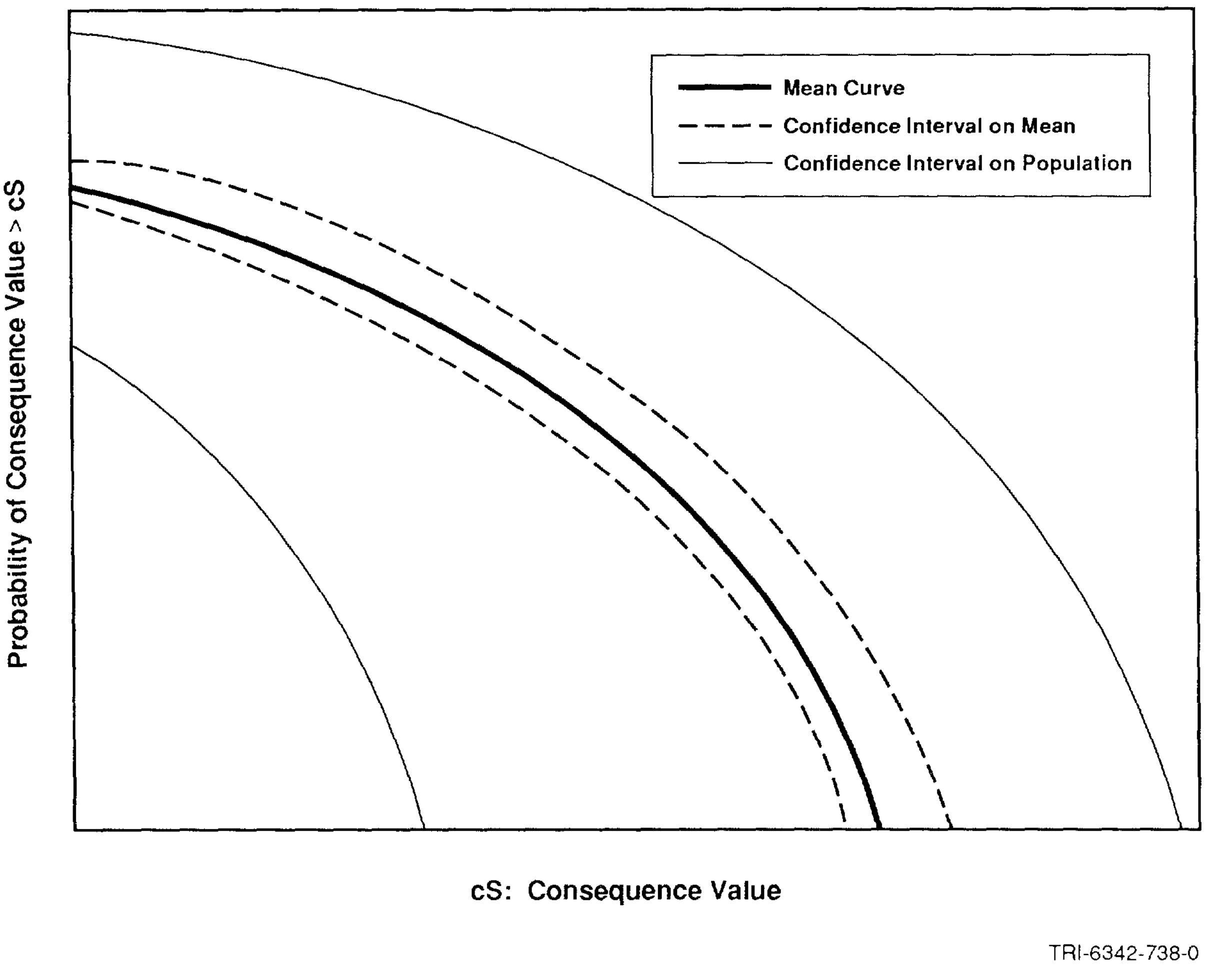

Figure 3-8. Example Confidence Bands for CCDFs (Helton et al., 1991).

of CCDFs. A single CCDF arises from the fact that a number of different occurrences have a real possibility of taking place. This type of uncertainty is referred to as stochastic variation in this report. A distribution of CCDFs arises from the fact that fixed, but unknown, quantities are needed in the estimation of a CCDF. The development of distributions that characterize what the values for these fixed quantities might be leads to a distribution of CCDFs. In essence, a performance assessment can be viewed as a very complex function that estimates a CCDF. Since there is uncertainty in the values of some of the input variables operated on by this function, there will also be uncertainty in the output variable produced by this function, where this output variable is a CCDF.

Both Kaplan and Garrick (1981) and a recent report by the International Atomic Energy Agency (IAEA) (1989) have been very careful to make a distinction between these two types of uncertainty. Specifically, Kaplan and Garrick distinguish between probabilities derived from frequencies and probabilities that characterize degrees of belief. Probabilities derived from frequencies correspond to the probabilities pS_i in Equation 3-1 while probabilities that characterize degrees of belief (i.e., subjective probabilities) correspond to the distributions indicated in Equation 3-5. The IAEA report distinguishes between what it calls Type A uncertainty and Type B uncertainty. The IAEA report defines Type A uncertainty to be stochastic variation; as such, this uncertainty corresponds to the frequency-based probability of Kaplan and Garrick and the pS_i of Equation 3-1. Type B uncertainty is defined to be uncertainty that is due to lack of knowledge about fixed quantities; thus, this uncertainty corresponds to the subjective probability of Kaplan and Garrick and the distributions indicated in Equation 3-5. This distinction has also been made by other authors, including Vesely and Rasmusen (1984), Paté-Cornell (1986) and Parry (1988).

As an example, the WIPP performance assessment includes subjective uncertainty in quantities such as solubility limits, retardation factors, and flow fields. Stochastic uncertainty enters into the analysis through the assumption that future exploratory drilling will be random in time and space (i.e., follow a Poisson process). However, the rate constant λ in the definition of this Poisson process is assumed to be imprecisely known. Thus, there is subjective uncertainty in a quantity used to characterize stochastic uncertainty.

A recent reassessment of the risk from commercial nuclear power plants performed by the U.S. Nuclear Regulatory Commission (U.S. NRC, 1990) has been very careful to preserve the distinction between these two types of uncertainty and provides an example of a very complex analysis in which a significant effort was made to properly incorporate and represent these two different types of uncertainty. Many of the results used for illustration in this chapter are adapted from that study. A similarly careful effort to represent uncertainty in performance assessment for radioactive waste disposal will greatly facilitate the performance and presentation of analyses intended to assess compliance with the EPA release limits.

3.1.4 RISK AND THE EPA LIMITS

As discussed in Chapter 2 of this volume, the EPA has promulgated the following standard for the long-term performance of geologic repositories for high-level and transuranic (TRU) wastes (1985):

> 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 on 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 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).

The term "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" (U.S. EPA, 1985, 191.12(k)). Further, "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" (U.S. EPA, 1985, 191.12(g)). The preceding requirements refer to Table 1 (Appendix A). This table is reproduced here as Table 3-1.

For a release to the accessible environment that involves a mix of radionuclides, the limits in Table 3-1 are used to define a normalized release for comparison with the release limits. Specifically, the normalized release for TRU waste is defined by

$$nR = \sum_i \left(Q_i/L_i\right) \left(1 \times 10^6 \text{ Ci}/C\right) \tag{3-8}$$

TABLE 3-1. RELEASE LIMITS FOR THE CONTAINMENT REQUIREMENTS (U.S. EPA, 1985, Appendix A, Table 1)

Radionuclide	Release limit L_i per 1000 MTHM* or other unit of waste (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

* Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

where

Q_i = cumulative release (Ci) of radionuclide i to the accessible environment during the 10,000-yr period following closure of the repository,

L_i = the release limit (Ci) for radionuclide i given in Table 3-1,

and

C = amount of TRU waste (Ci) emplaced in the repository.

For the 1991 WIPP performance assessment, C = 11.87 x 10^6 Ci.

In addition to the previously stated Containment Requirements, the EPA expressly identifies the need to consider the impact of uncertainties in calculations performed to show compliance with these requirements. Specifically, the following statement is made:

> ...whenever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with [section] 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 [section] 191.13 if this single distribution function meets the requirements of [section] 191.13(a) (U.S. EPA, 1985, p. 38088).

The representation for risk in Equation 3-1 provides a conceptual basis for the calculation of the "complementary cumulative distribution function" for normalized releases specified in the EPA standard. Further, this representation provides a structure that can be used for both the incorporation of uncertainties and the representation of the effects of uncertainties.

With respect to the EPA Containment Requirements (§ 191.13(a)), the sets S_i, $i = 1, \ldots, nS$, appearing in Equation 3-1 are simply the scenarios selected for consideration. Ultimately, these scenarios S_i derive from the significant "processes" and "events" referred to in the Standard. These scenarios S_i will 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 preceding ideas are now illustrated with a hypothetical example involving $nS=8$ scenarios $S_1, S_2, \ldots, S_8$. 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 3-1 could be constructed for comparison with the EPA release limits. Unfortunately, neither the pS_i nor the $\mathbf{cS}_i$ are likely to be known with certainty. When this is incorporated into the representation in Equation 3-1, the set R can be expressed as

$$R(\mathbf{x}) = \{(S_i,\ pS_i(\mathbf{x}),\ \mathbf{cS}_i(\mathbf{x})),\ i = 1,\ \ldots,\ nS = 8\}, \qquad (3\text{-}9)$$

where $\mathbf{x}$ represents a vector of imprecisely known variables required in the estimation of the pS_i and the $\mathbf{cS}_i$. For this example, the S_i are assumed to be fixed and thus are not represented as functions of $\mathbf{x}$ as is done for the more general case shown in Equation 3-4. The effect of uncertainties in $\mathbf{x}$ can be investigated by generating a random or Latin hypercube sample (McKay et al., 1979) from the variables contained in $\mathbf{x}$. This creates a sequence of sets $R(\mathbf{x})$ of the form

$$R(\mathbf{x}_k) = \{(S_i,\ pS_i(\mathbf{x}_k),\ \mathbf{cS}_i(\mathbf{x}_k)),\ i = 1,\ \ldots,\ nS = 8\} \qquad (3\text{-}10)$$

for $k = 1, \ldots, nK$, where $\mathbf{x}_k$ is the value for $\mathbf{x}$ in sample element k and nK is the number of elements in the sample.

As previously illustrated in Figure 3-1, a CCDF can be constructed for each sample element and each consequence measure contained in $\mathbf{cS}$. Figure 3-9 shows what the resultant distribution of CCDFs for the normalized EPA release might look like. 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 3-9 reflects the distributions assigned to the sampled variables in $\mathbf{x}$. 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 sample of size nK=40, so 40 CCDFs are displayed, one for each sample element. 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.

Figure 3-9 is rather cluttered and hard to interpret. As discussed in conjunction with Figure 3-6, mean and percentile curves can be used to summarize the family of CCDFs in Figure 3-9. The outcome of this construction is shown in Figure 3-10, which shows the resultant mean curve and the 90th, 50th (median), and 10th percentile curves. The mean curve has generally been proposed for showing compliance with § 191.13(a) (e.g., Cranwell et al., 1990; Cranwell et al., 1987; Hunter et al., 1986).

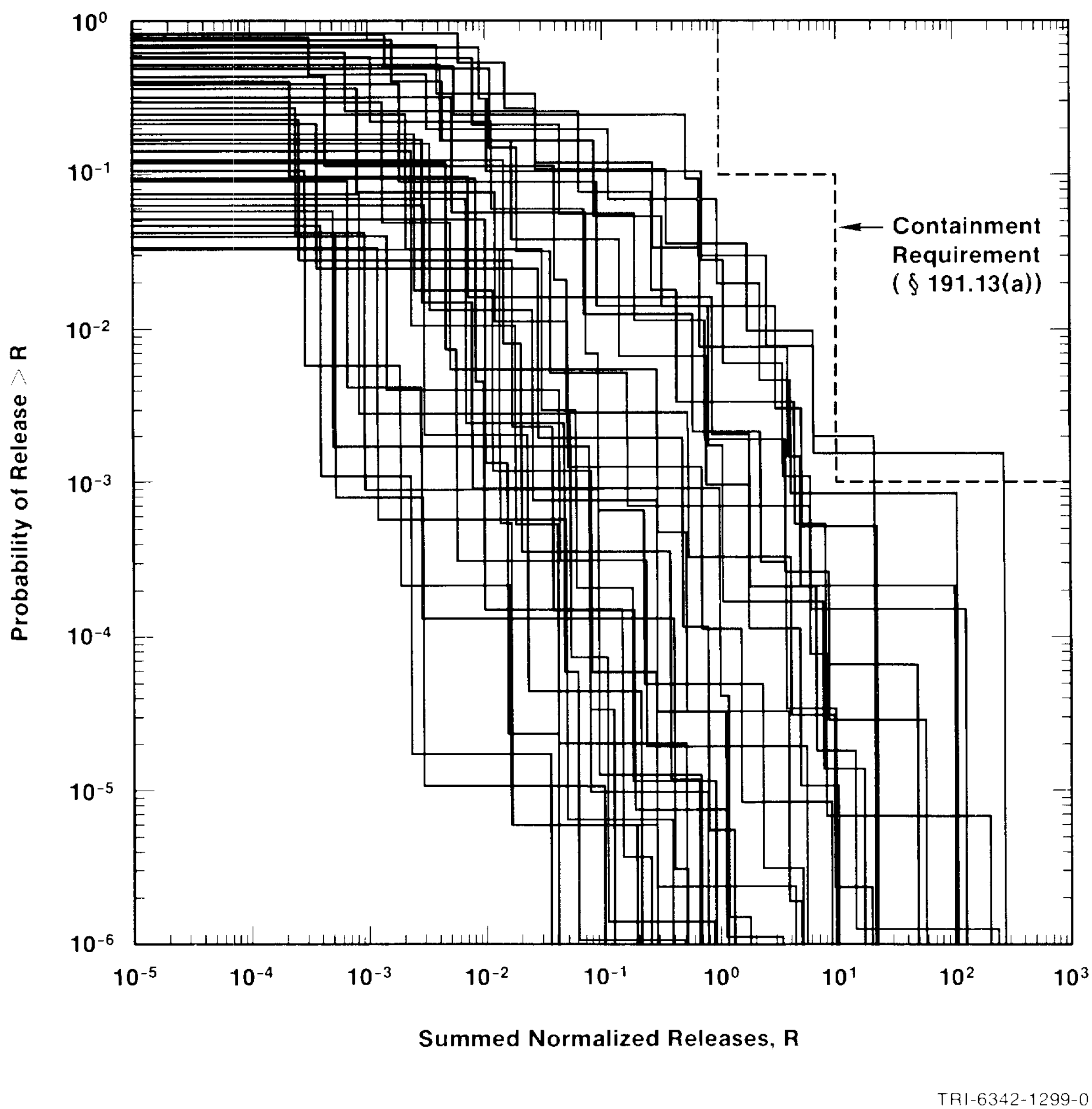

Figure 3-9. Hypothetical Distribution of CCDFs for Comparison with the Containment Requirements (§ 191.13(a)).

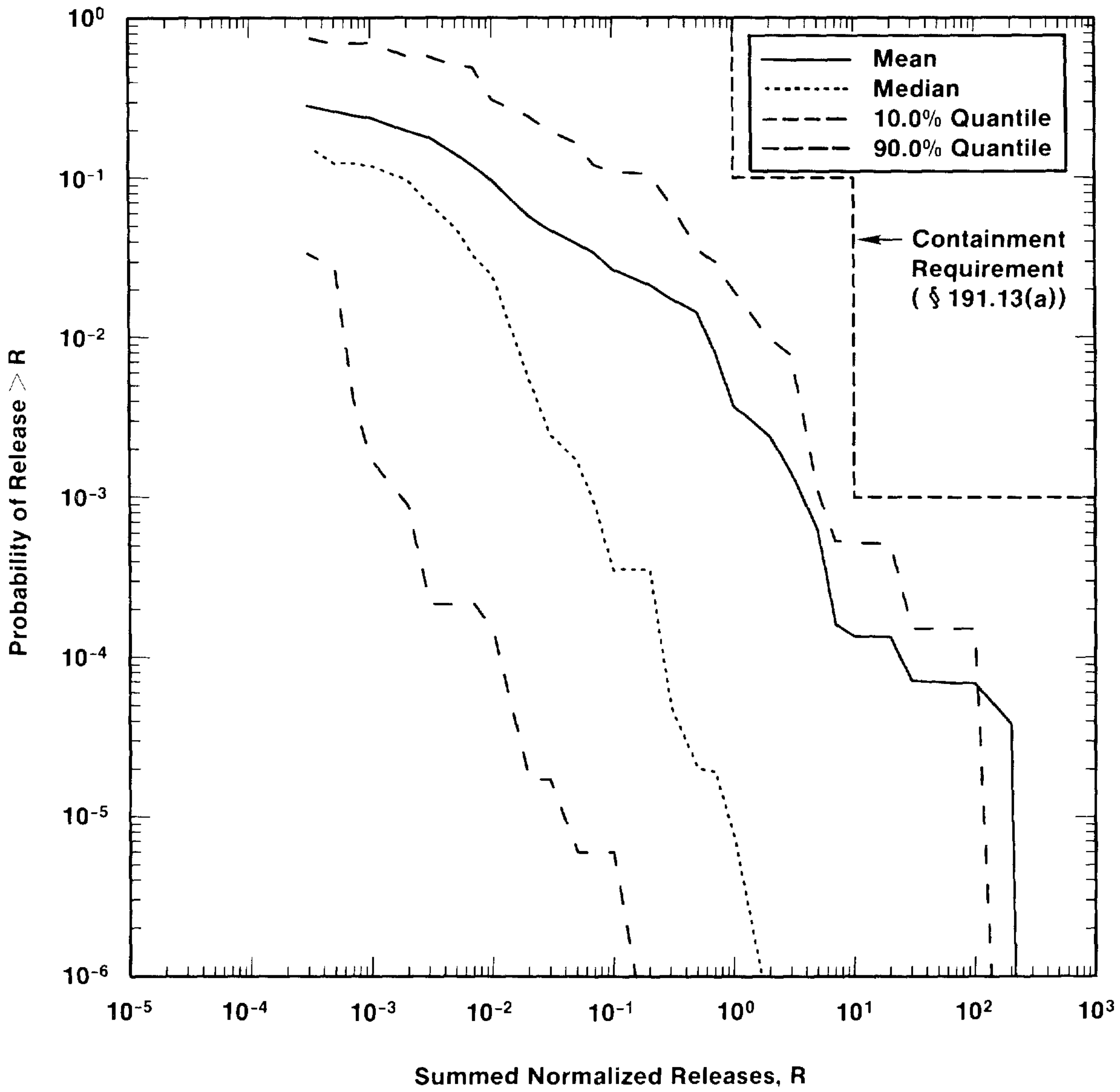

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Figure 3-10. Mean and Percentile Curves for the Example Distribution of CCDFs Shown in Figure 3-9.

Now that Figures 3-9 and 3-10 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 uncertain, the probabilities of exceeding these release limits can never be known with certainty. However, by placing distributions on imprecisely known quantities, distributions for these probabilities can 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 the example, an estimated distribution of probabilities at which a normalized release of 1 will be exceeded can be obtained by drawing a vertical line through 1 on the abscissa in Figure 3-9. This line will cross the 40 CCDFs generated in this example to yield a distribution of 40 exceedance probabilities. A similar construction can be performed for a normalized release of 10. Means (actually, estimates for the expected value of the true distribution, conditional on the assumptions of the 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 3-10.

The EPA suggests 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 3-1. The EPA further suggests 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 3-10 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 3-10 could be used. However, whenever a distribution of curves is reduced to a single curve, information on uncertainty is lost.

Replicated sampling can characterize the uncertainty in an estimated mean CCDF or other summary curve. However, representing the uncertainty in an estimated value in this way is quite different from displaying the variability or uncertainty in the population from which the estimate is derived (Figure 3-9). For example, the uncertainty in the estimated mean curve in Figure 3-10 is 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 3-11 shows the family of CCDFs that results when the same sample used to construct the CCDFs in Figure 3-9 is used but the individual scenario probabilities are fixed. In this case, the values for the pS_i do not change from sample element to sample element, but the values for 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 3-12. The hypothetical results on which Figures 3-9 and 3-11 are based were constructed so that the normalized release for scenario S_{i+1} is greater than the normalized release for scenario S_i for each sample element. The step heights associated with the individual scenarios in Figure 3-11 would still be the same if this ordering did not exist, but there would be a more complex mixing of step heights.

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 3-13 gives a schematic representation for this construction approach. This approach is applicable to situations in which the scenario probabilities are known and, in this case, yields the same mean CCDF as shown in Figure 3-12.

3.1.5 PROBABILITY AND RISK

A brief discussion of how the concepts associated with a formal development of probability relate to the definition of risk in Equation 3-1 is now given. The intent is to emphasize the ideas involved rather than mathematical rigor. A more detailed development of the mathematical basis of probability can be found in numerous texts on probability theory (e.g., Feller, 1971; Ash, 1972). In addition, several excellent discussions of different conceptual interpretations of probability are also available (Barnett, 1982; Weatherford, 1982; Apostolakis, 1990). A familiarity with the basic ideas in the mathematical development of probability greatly facilitates an understanding of scenario development.

A formal development of probability is based on the use of sets. The first of these sets is called the sample space, which is the set of all possible outcomes associated with the particular process or situation under consideration. In the literature on probability, these individual outcomes are referred to as elementary events. As an example, performance assessment

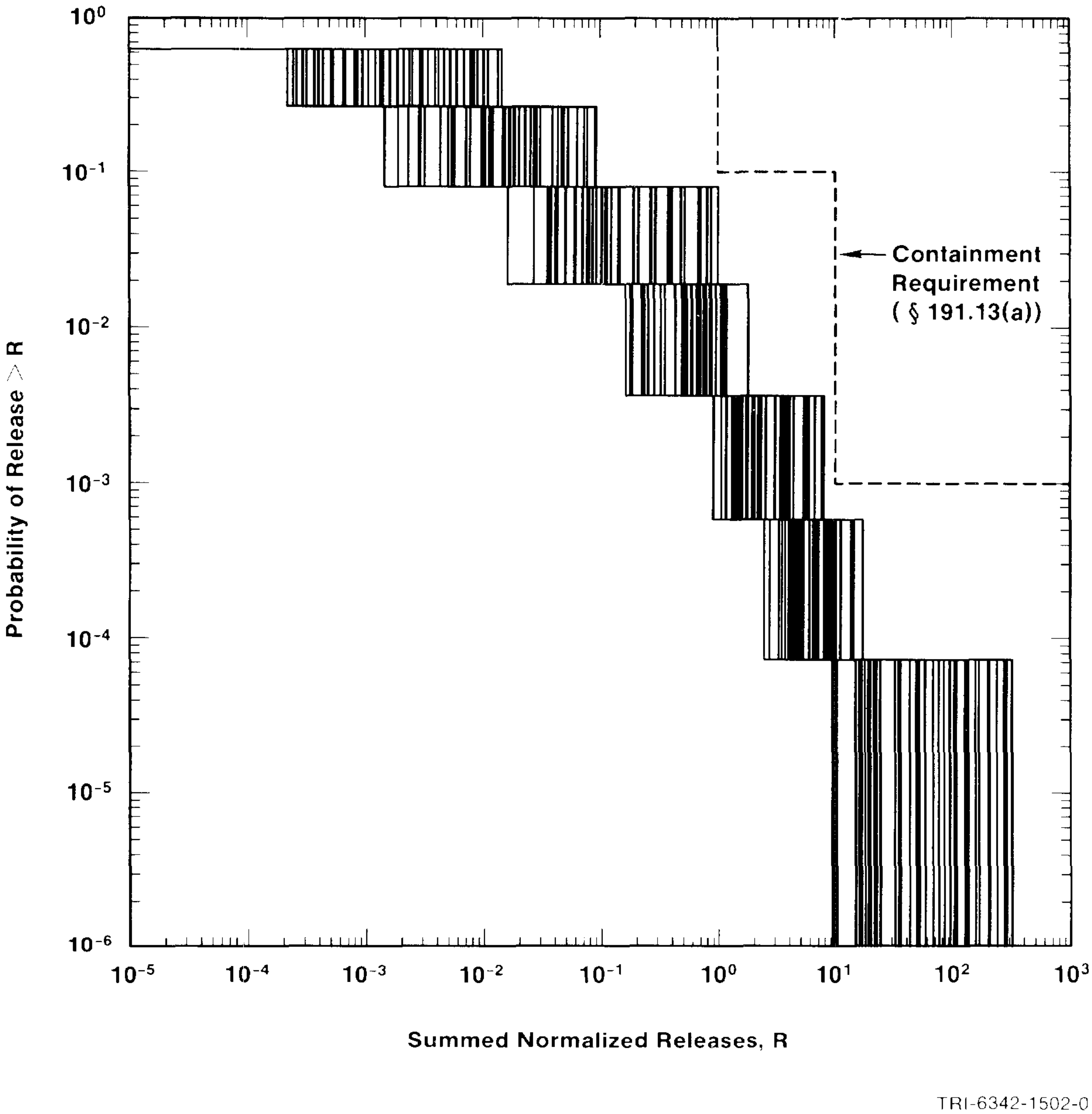

Figure 3-11. Hypothetical Distribution of CCDFs Generated for Comparison with the Containment Requirements in Which the Scenario Probabilities Are the Same for All Sample Elements.

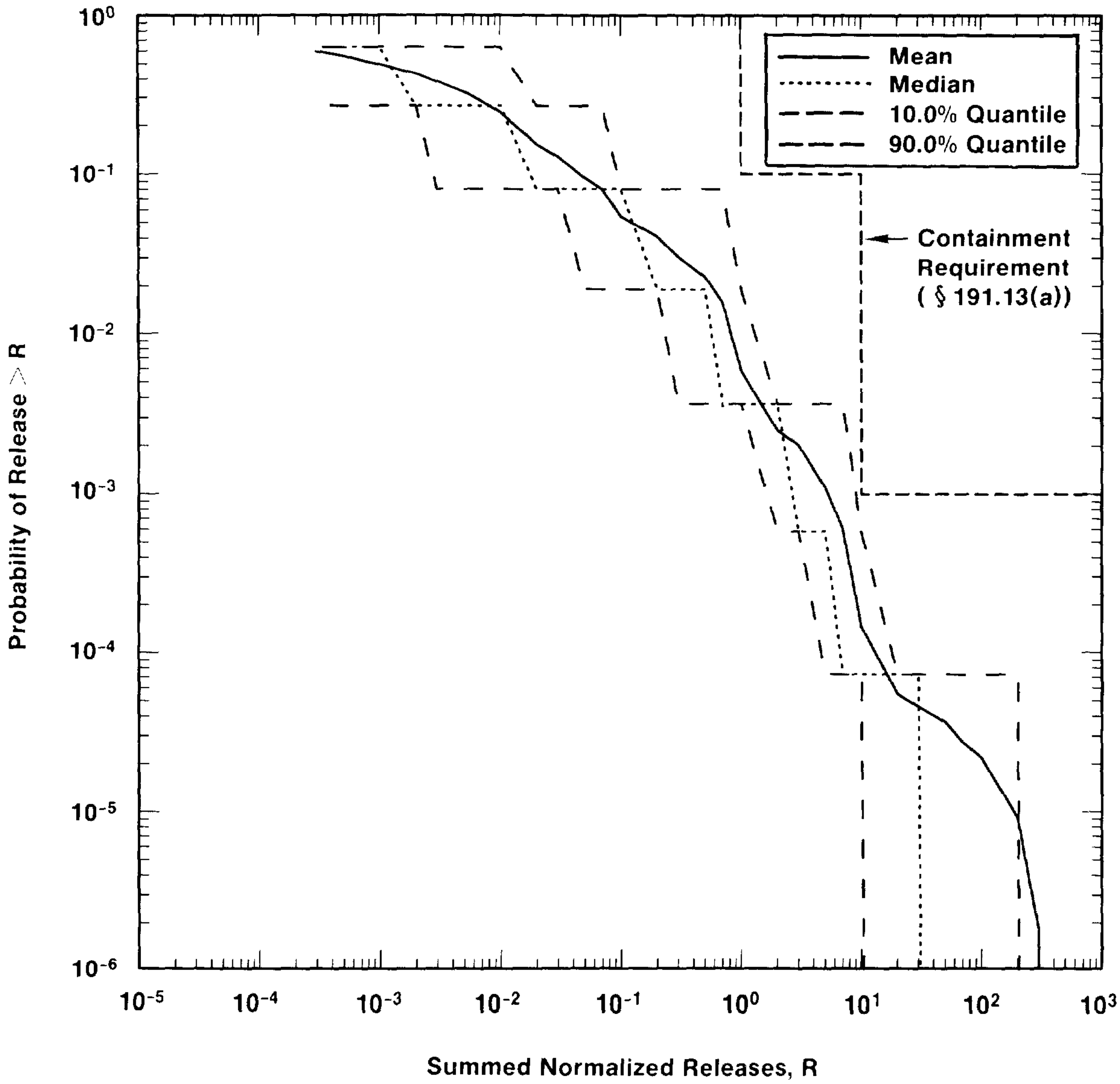

Figure 3-12. Mean and Percentile Curves for the Example Distribution of CCDFs Shown in Figure 3-11.

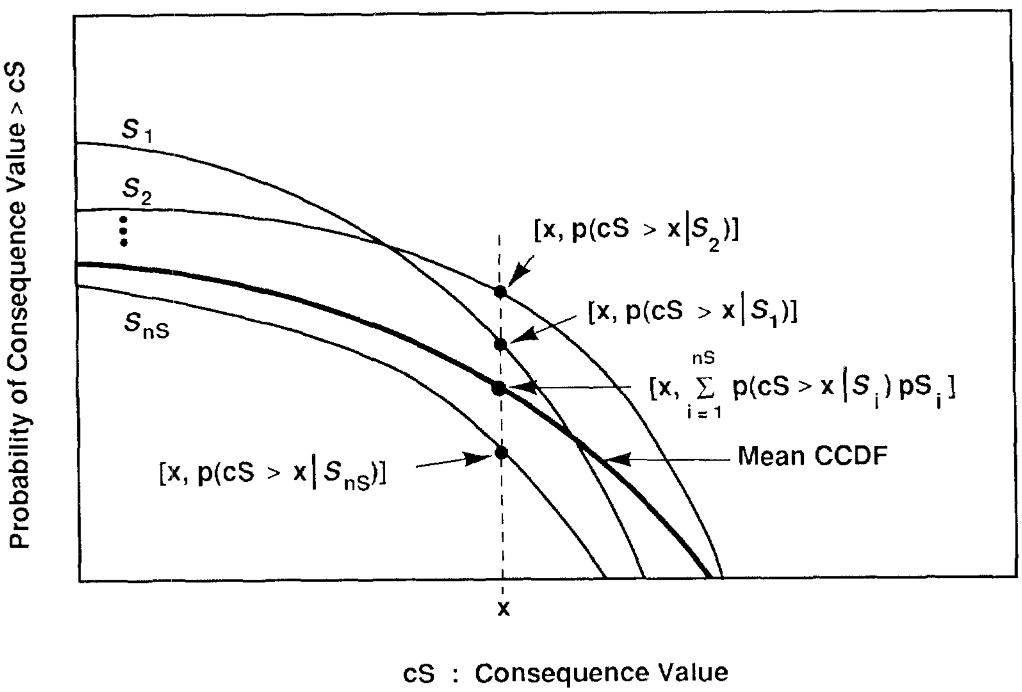

Figure 3-13. Construction of Mean CCDF from Conditional CCDFs. The expression p(cS>x|S_i) is the probability of a normalized release exceeding x over 10,000 years given that scenario S_i has occurred. The ordinate displays conditional probability for the CCDFs for the individual scenarios S_i and probability 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 et al., 1991).

at the WIPP involves the characterization of the behavior of this site over a 10,000-yr period beginning at the decommissioning of the facility. Thus, the sample space would consist of all possible 10,000-yr "histories" at the WIPP for this time period. To avoid confusion with the regulatory use of the word "event," outcome or history is used for elementary event in this report. More specifically, the sample space is the set S defined by

$$S = \{x: x \text{ a single 10,000-yr history beginning at decommissioning of the WIPP}\}. \quad (3\text{-}11)$$

Each 10,000-yr history is complete in the sense that it includes a full specification, including time of occurrence, for everything of importance to performance assessment that happens in this time period. In the terminology of Cranwell et al. (1990), each history would contain a characterization for a specific sequence of "naturally occurring and/or human-induced conditions that represent realistic future states of the repository, geologic systems, and ground-water flow systems that could affect the release and transport of radionuclides from the repository to humans."

In general, the sample space will contain far too many outcomes to permit a meaningful development of probability to be based on the outcomes themselves. Crudely put, the individual outcomes are so unlikely to occur that probabilities cannot be assigned to their individual occurrences in a way that leads to a useful probabilistic structure that permits a calculation of probabilities for groups of outcomes. As a result, it is necessary to group the outcomes into sets called events, where each event is a subset of the sample space, and then to base the development of probability on these sets. An event, as used in a formal development of probability, corresponds to what is typically called a scenario in performance assessment (i.e., the S_i appearing in Equation 3-1).

An example of an event E in the probabilistic development for the WIPP would be the set of all time histories in which the first borehole to penetrate the repository occurs between 5000 and 10,000 years after decommissioning. That is,

$$E = \{x: x \text{ a 10,000-yr history at the WIPP in which the first borehole to penetrate the repository occurs between 5000 and 10,000 years after decommissioning}\}. \quad (3\text{-}12)$$

Due to the many ways in which the outcomes in a sample space might be sorted, the number of different events is infinite. In turn, each event is composed of many outcomes or, in the case of the WIPP, many 10,000-yr histories. Thus, events are "larger" than the individual outcomes contained in the sample space.

As another example, Cranwell et al. (1990) define a scenario (i.e., an event as used in the formal development of probability) to be "a set of naturally occurring and/or human-induced conditions that represent realistic future states of the repository, geologic systems, and ground-water flow systems that could affect the release and transport of radionuclides from the repository to humans." As their development shows, they include all possible ways in which this set of "conditions" could occur. Thus, they are actually using the set of all time histories in which this set of conditions occurs as their scenario. Their logic diagram for constructing scenarios (Cranwell et al., 1990, Figure 2) is equivalent to forming intersections of sets of time histories.

Probabilities are defined for events rather than for the individual outcomes in the sample space. Further, probabilities cannot be meaningfully developed for single events in isolation from other events but rather must be developed in the context of a suitable collection of events. The basic idea is to develop a logically complete representation for probability for a collection of events that is large enough to contain all events that might reasonably be of interest but, at the same time, is not so large that it contains events that result in intractable mathematical properties. As a result, the development of probability is usually restricted to a collection $\mathcal{S}$ of events that has the following two properties:

(1) if E is in $\mathcal{S}$, then E^c is in $\mathcal{S}$, where the superscript c is used to denote the complement of E,

and

(2) if $\{E_i\}$ is a countable collection of events from $\mathcal{S}$, then $\cup_i E_i$ and $\cap_i E_i$ also belong to $\mathcal{S}$.

A collection or set $\mathcal{S}$ satisfying the two preceding conditions is called a σ-algebra or a Borel algebra. The significance of such a set is that all the familiar operations with sets again lead to a set in it (i.e., it is closed with respect to set operations such as unions, intersections, and complements).

As noted earlier, an event in the probabilistic development corresponds to what is typically called a scenario in performance assessment. Thus, in the context of performance assessment, the set $\mathcal{S}$ would contain all allowable scenarios. However, for a given sample space S, the definition of $\mathcal{S}$ is not unique. This results from the fact that it is possible to develop the events in $\mathcal{S}$ at many different levels of detail. As described in the preceding paragraph, $\mathcal{S}$ is required to be a σ-algebra. The importance of this requirement with respect to performance assessment is that it results in the complements, unions, and intersections of scenarios also being scenarios with defined probabilities.

Given that a suitably restricted set $\mathcal{S}$ is under consideration (i.e., a σ-algebra), the probabilities of the events in $\mathcal{S}$ are defined by a function p such that

(1) $p(S) = 1$,

(2) if E is in $\mathcal{S}$, then $0 \leq p(E) \leq 1$,

and

(3) if $E_1, E_2, \ldots$ is a sequence of disjoint sets (i.e., $E_i \cap E_j = \emptyset$ if $i \neq j$) from $\mathcal{S}$, then $p(\cup_i E_i) = \Sigma_i\, p(E_i)$.

All of the standard properties of probabilities can be derived from this definition.

An important point to recognize is that probabilities are not defined in isolation. Rather, there are three elements to the definition of probability: the sample space S, a collection $\mathcal{S}$ of subsets of S, and the function p defined on $\mathcal{S}$. Taken together, these quantities form a triple $(S, \mathcal{S}, p)$ called a probability space and must be present, either implicitly or explicitly, in any reasonable development of the concept of probability.

Now that the formal ideas of probability theory have been briefly introduced, the representation for risk in Equation 3-1 is revisited. As already indicated in Equation 3-11, the sample space in use when the EPA release limit for the WIPP is under consideration is the set of all possible 10,000-yr histories that begin at the decommissioning of the facility. The sets S_i appearing in Equation 3-1 are subsets of the sample space, and thus the pS_i are probabilities for sets of time histories. If an internally consistent representation for probability is to be used, the S_i must be members of a suitably defined set $\mathcal{S}$, and a probability function p must be defined on $\mathcal{S}$. Typically, the set $\mathcal{S}$ is not explicitly developed. However, if there is nothing inherently inconsistent with the probability assignments already made in Equation 3-1, it is possible to construct a set $\mathcal{S}$ and an associated probability function p such that the already assigned probabilities for the S_i remained unchanged. However, this extension is not unique unless it is made to the smallest σ-algebra that contains the already defined scenarios. Such an extension permits the assignment of probabilities to new scenarios in a manner that is consistent with the probabilities already assigned to existing scenarios.

The most important idea that the reader should take out of this section is that scenarios (i.e., the sets S_i in Equation 3-1) are sets of time histories. In particular, scenarios are arrived at by forming sets of similar time histories. There is no inherently correct grouping, and the probabilities associated with individual scenarios S_i can always be reduced by using a finer grouping. Indeed, as long as low-probability S_i are not thrown away, the use of more but lower probability S_i will improve the resolution in the estimated CCDF shown in Figure 3-1. Further, as an integrated release or some other consequence result must be calculated for each scenario S_i, the use of more S_i also results in more detailed specification of the calculations that must be performed for each scenario.

For example, a scenario S_i for the WIPP might be defined by

$$S_i = \{x:\ \text{x a 10,000-yr history at the WIPP beginning at decommissioning in which a single borehole occurs}\}. \tag{3-13}$$

A more refined definition would be

$$S_{ik} = \{x:\ \text{x a 10,000-yr history at the WIPP beginning at decommissioning in which a single borehole occurs between } (i-1)*10^3 \text{ and } i*10^3 \text{ yrs and no boreholes occur during any other time interval}\}. \tag{3-14}$$

Then,

$$S_{ik} \subset S_i,\ i = 1, \ldots, 10, \text{ and } S_i = \bigcup_{k=1}^{10} S_{ik}. \tag{3-15}$$

Thus, S_i and $\cup_k S_{ik}$ contain the same set of time histories. However, the individual S_{ik} contain smaller sets of time histories than does S_i. In terms of performance assessment, each S_{ik} describes a more specific set of conditions that must be modeled than does S_i. The estimated CCDF in Figure 3-1 could be constructed with either S_i or the S_{ik}, although the use of the S_{ik} would result in less aggregation error and thus provide better resolution in the resultant CCDF.

The S_i appearing in the definition of risk in Equation 3-1 should be developed to a level of resolution at which it is possible to view the analysis for each S_i as requiring a fixed, but possibly imprecisely known, vector **x** of variable values. Ultimately, this relates to how the set $\mathcal{S}$ in the formal definition of probability will be defined. When a set S_i is appropriately defined, it should be possible to use the same model or models and the same vector of variable values to represent every occurrence (e.g., a 10,000-yr time history for WIPP) in S_i. In contrast, S_i is "too large" when this is not possible. For example, the set S_i in Equation 3-13 is probably "too large" for the assumption that a fixed time of intrusion (e.g., 5000 yr) is appropriate for all 10,000-yr histories contained in S_i, while a similar assumption about time of intrusion (e.g., $(k-1/2)*10^3$ yr) might be appropriate for S_{ik} as defined in Equation 3-14. A major challenge in structuring a performance assessment is to develop the sets S_i appearing in Equation 3-1, and hence the underlying probability space, at a suitable level of resolution.

3.2 Definition of Scenarios

As indicated in Equation 3-1, the outcome of a performance assessment for WIPP can be represented by a set of ordered triples. The first element of each triple, denoted S_i, is a set of similar occurrences or, equivalently, a scenario. As a result, an important part of the WIPP performance assessment is the development of scenarios.

The WIPP performance assessment uses a two stage procedure for scenario development. The purpose of the first stage is to develop a comprehensive set of scenarios that includes all occurrences that might reasonably take place at the WIPP. The result of this stage is a set of scenarios that summarize what might happen at the WIPP. These scenarios provide a basis for discussing the future behavior of the WIPP and a starting point for the second stage of the procedure, which is the definition of scenarios at a level of detail that is appropriate for use with the computational models employed in the WIPP performance assessment.

The first stage is directed at understanding what might happen at the WIPP and answering completeness questions. The second stage is directed at organizing the actual calculations that must be performed to obtain the consequences $\mathbf{c}S_i$ appearing in Equation 3-1, and as a result, must provide a structure that both permits the $\mathbf{c}S_i$ to be calculated at a reasonable cost and holds the amount of aggregation error that enters the analysis to a reasonable level. These two stages are now discussed in more detail.

3.2.1 DEFINITION OF SUMMARY SCENARIOS

The first stage of scenario definition for the WIPP performance assessment uses a five-step procedure proposed by Cranwell et al. (1990). The steps in this procedure are: (1) compiling or adopting a "comprehensive" list of events[1] 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 CCDF used for comparisons with EPA release limits.

Conceptually, the purpose of the first three steps is to develop the sample space S appearing in a formal definition of probability. As indicated in Equation 3-11, the sample space for the WIPP performance assessment is the set of all possible 10,000-yr histories beginning at decommissioning of the facility. The development of S is described in Chapter 4. For the 1991 performance assessment, this development lead to a set S in which all creditable disruptions were due to drilling intrusions.

Once the sample space S is developed, it is necessary to partition S into the subsets, or scenarios, S_i appearing in Equation 3-1. This is the fourth step in the scenario development procedure. As explained in Section 3.1.5-Probability and Risk, the S_i belong to a set $\mathcal{S}$ that, in concept, contains all scenarios for which probabilities will be defined.

The S_i are developed by decomposing S with logic diagrams of the form shown in Figure 3-14. The logic diagram shown in Figure 3-14 starts with the following three scenarios (i.e., subsets of S):

$$TS = \{x: \text{ x a 10,000-yr history in which subsidence results due to solution mining of potash}\}, \tag{3-16}$$

$$E1 = \{x: \text{ x a 10,000-yr history in which one or more boreholes pass through the repository and into a brine pocket}\}, \tag{3-17}$$

and

$$E2 = \{x: \text{ x a 10,000-yr history in which one or more boreholes pass through the repository without penetration of a brine pocket}\}. \tag{3-18}$$

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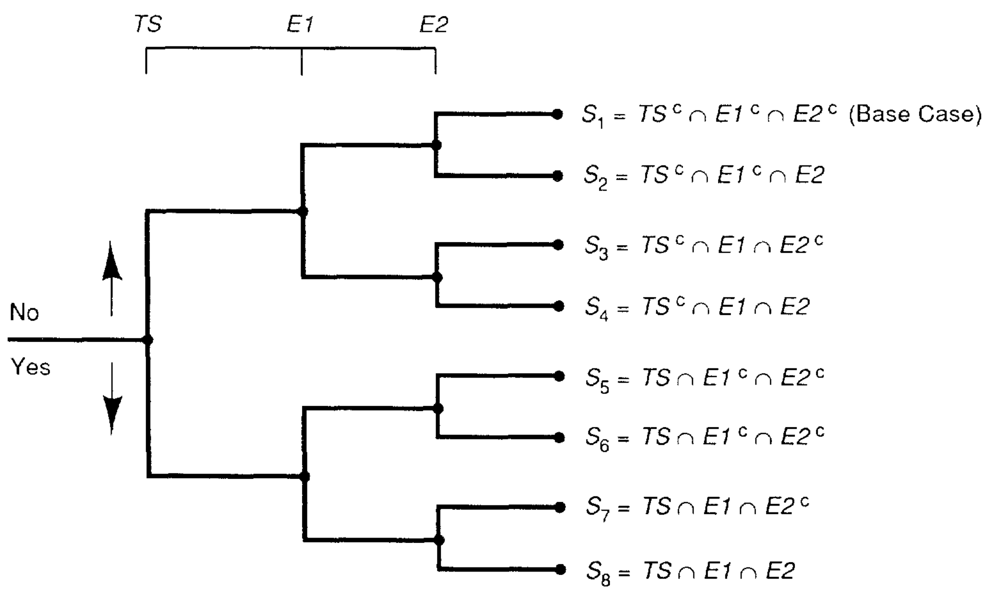
[1] Cranwell et al. (1990) do not use the word "event" in the formal probabilistic sense used in Section 3.1.5-Probability and Risk, although their usage can be interpreted in that formal sense.



TS = {x: Subsidence Resulting From Solution Mining of Potash}

E1 = {x: One or More Boreholes Pass Through a Waste Panel and into a Brine Pocket}

E2 = {x: One or More Boreholes Pass Through a Waste Panel Without Penetration of a Brine Pocket}

Superscript c (e.g., TS^c) Denotes Set Complement

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Figure 3-14. Example Use of Logic Diagram to Construct Summary Scenarios.

Additional scenarios are then defined by the paths through the logic diagram shown in Figure 3-13. This results in the decomposition of S into the following eight scenarios:

$$S_1 = TS^c \cap E1^c \cap E2^c,\ S_2 = TS^c \cap E1^c \cap E2,\ S_3 = TS^c \cap E1 \cap E2^c,\ S_4 = TS^c \cap E1 \cap E2,$$

$$S_5 = TS \cap E1^c \cap E2^c,\ S_6 = TS \cap E1^c \cap E2,\ S_7 = TS \cap E1 \cap E2^c,\ S_8 = TS \cap E1 \cap E2, \quad (3\text{-}19)$$

where the superscript c denotes the complement of a set. These eight scenarios constitute a complete decomposition of S in the sense that

$$S = \bigcup_{i=1}^{8} S_i. \quad (3\text{-}20)$$

The development of these scenarios is discussed and more detail on their individual characteristics is given in Chapter 4 of this volume.

The last step in the development procedure is screening to remove unimportant scenarios. As discussed in Chapter 4 of this volume, screening did not remove any of the preceding eight scenarios from further consideration for the 1991 WIPP performance assessment, although the assumption is made that scenario *TS* has no impact on releases from the repository for the 1991 performance assessment. The effect of this assumption will be evaluated in the 1992 performance assessment.

3.2.2 DEFINITION OF COMPUTATIONAL SCENARIOS

Although the preceding decomposition of S is useful for discussion and the development of an understanding of what is important at the WIPP, a more detailed decomposition is needed for the actual calculations that must be performed to determine scenario consequences (i.e., the $\mathbf{cS}_i$ as shown in Equation 3-1) and to provide a basis for CCDF construction. To provide more detail for the determination of both scenario probabilities and scenario consequences, the scenarios on which the actual CCDF construction is based for the WIPP performance assessment are defined on the basis of (1) number of drilling intrusions, (2) time of the drilling intrusions, (3) whether or not a single waste panel is penetrated by two or more boreholes, of which at least one penetrates a brine pocket and at least one does not, and (4) the activity level of the waste penetrated by the boreholes. The purpose of this decomposition is to provide a systematic coverage of what might reasonably happen at the WIPP.

The preceding scenario construction procedure starts with the division of the 10,000-yr time period appearing in the EPA regulations into a sequence

$$[t_{i-1}, t_i], \; i = 1, 2, \ldots, nT, \tag{3-21}$$

of disjoint time intervals. When activity loading is not considered, these time intervals lead to scenarios of the form

$$S(\mathbf{n}) = \{x: x \text{ an element of } S \text{ for which exactly } n(i) \text{ intrusions occur in time interval } [t_{i-1}, t_i] \text{ for } i=1, 2, \ldots, nT\} \tag{3-22}$$

and

$$S^{+-}(t_{i-1},t_i) = \{x: x \text{ an element of } S \text{ involving two or more boreholes that penetrate the same waste panel during the time interval } [t_{i-1}, t_i], \text{ at least one of these boreholes penetrates a pressurized brine pocket and at least one does not penetrate a pressurized brine pocket}\}, \tag{3-23}$$

where

$$\mathbf{n} = [n(1), n(2), \ldots, n(nT)]. \tag{3-24}$$

When activity loading is considered, the preceding time intervals lead to scenarios of the form

$$S(\mathbf{l},\mathbf{n}) = \{x: x \text{ an element of } S(\mathbf{n}) \text{ for which the } j^{th} \text{ borehole encounters waste of activity level } \ell(j) \text{ for } j=1, 2, \ldots, nBH, \text{ where nBH is the total number of boreholes associated with a time history in } S(\mathbf{n})\} \tag{3-25}$$

and

$$S^{+-}(\mathbf{l};t_{i-1},t_i) = \{x: x \text{ an element of } S^{+-}(t_{i-1}, t_i) \text{ for which the } j^{th} \text{ borehole encounters waste of activity level } \ell(j) \text{ for } j=1, 2, \ldots, nBH, \text{ where nBH is the total number of boreholes associated with a time history in } S^{+-}(t_{i-1},t_i)\}, \tag{3-26}$$

where

$$\mathbf{l} = [\ell(1), \ell(2), \ldots, \ell(nBH)] \text{ and } nBH = \sum_{i=1}^{nT} n(i). \tag{3-27}$$

Further refinements on the basis of whether or not subsidence occurs and whether or not individual boreholes penetrate pressurized brine pockets are also possible. However, at present, these distinctions do not appear to be important in the determination of scenario consequences and, as a result, are not included in calculations performed for the 1991 WIPP performance assessment. In essence, the computational scenarios defined in Equation 3-21 through Equation 3-27 are defining an important sampling strategy that covers the stochastic or type A uncertainty that is characterized by the scenario probabilities pS_i appearing in Equation 3-1. Additional information on the definition of computational scenarios is given in Volume 2, Chapter 3 of this report.

3.3 Determination of Scenario Probabilities

The second element of the ordered triples shown in Equation 3-1 is the scenario probability pS_i. As with scenario definition, the probabilities pS_i have been developed at two levels of detail.

3.3.1 PROBABILITIES FOR SUMMARY SCENARIOS

The first level was for use with the summary scenarios described in Section 3.2.1-Definition of Summary Scenarios. The logic used to construct these probabilities is shown in Figures 4-10 and 4-11 in Chapter 4 of this volume. The construction shown in Figure 4-10 is based on a classical probability model in which alternative occurrences of unknown probability are assumed to have equal probability. The construction shown in Figure 4-11 is based on the use of a Poisson model. Additional discussion of these probability estimation procedures is given in Guzowski (1991). Further, Apostolakis et al. (1991) provide an extensive discussion of techniques for determining probabilities in the context of performance assessment for radioactive waste disposal.

In the WIPP performance assessment, probabilities are assigned to summary scenarios to assist in completeness arguments and to provide guidance with respect to what parts of the sample space must be considered in constructing CCDFs for comparison with the EPA release limits. The probabilities in Figure 4-11 were used to construct CCDFs for the 1990 preliminary comparison (Bertram-Howery et al., 1990). The probabilities used in the present report are now described.

3.3.2 PROBABILITIES FOR COMPUTATIONAL SCENARIOS

The second level of probability definition was for use with the computational scenarios described in Section 3.2.2-Definition of Computational Scenarios.

These are the probabilities that will actually be used in the construction of CCDFs for comparison with the EPA release limits. These probabilities are based on the assumption that the occurrence of boreholes through the repository follows a Poisson process with a rate constant λ. The probabilities $pS(\mathbf{n})$ and $pS(\mathbf{l},\mathbf{n})$ for the scenarios $S(\mathbf{n})$ and $S(\mathbf{l},\mathbf{n})$ are given by

$$pS(\mathbf{n}) = \left\{ \prod_{i=1}^{nT} \left[\frac{\lambda^{n(i)} \left(t_i - t_{i-1}\right)^{n(i)}}{n(i)!} \right] \right\} \exp\left[-\lambda\left(t_{nT} - t_0\right)\right] \tag{3-28}$$

and

$$pS(\mathbf{l},\mathbf{n}) = \left\{ \prod_{j=1}^{nBH} pL_{\ell(j)} \right\} pS(\mathbf{n}), \tag{3-29}$$

where $\mathbf{n}$ and $\mathbf{l}$ are defined in Equations 3-24 and 3-27, respectively, and pL_ℓ is the probability that a randomly placed borehole through a waste panel will encounter waste of activity level ℓ. The rate constant λ is a sampled variable in the 1991 WIPP performance assessment. Table 3-2 provides an example of probabilities $pS(\mathbf{n})$ calculated as shown in Equation 3-28 with $\lambda = 3.28 \times 10^{-4}\ yr^{-1}$ for the time interval from 100 to 10,000 yr, which corresponds to the maximum drilling rate suggested for use by the EPA. Because the Standard allows for 100 yr of active institutional control, λ has been set equal to zero for the time interval from 0 to 100 yr. Similar, but more involved, equations are used to obtain $pS^{+-}(t_{i-1}, t_i)$ and $pS^{+-}(\mathbf{l};t_{i-1}, t_i)$.

The formulas for determining $pS(\mathbf{n})$, $pS(\mathbf{l},\mathbf{n})$, $pS^{+-}(t_{i-1}, t_i)$, and $pS^{+-}(\mathbf{l};t_{i-1}, t_i)$ are derived in Volume 2, Chapter 2 of this report under the assumption that drilling intrusions follow a Poisson process (i.e., are random in time and space). The derivations are general and include both the stationary (i.e., constant λ) and nonstationary (i.e., time-dependent λ) cases.

3.4 Calculation of Scenario Consequences

The two preceding sections have discussed the development of scenarios S_i and their probabilities pS_i at two levels of detail. First, scenarios were considered at a summary level. This provides a fairly broad characterization of scenarios and their probabilities and thus provides a basis for general discussions of what might happen at the WIPP. Second, scenarios involving drilling intrusions were considered at a much finer level of detail. This additional detail facilitates the necessary calculations that must be performed to determine the scenario consequences $\mathbf{cS}_i$.

TABLE 3-2. PROBABILITIES FOR COMBINATIONS OF INTRUSIONS OVER 10,000 YRS FOR $\lambda = 0$ FROM 0 TO 100 YRS, $\lambda = 3.28 \times 10^{-4}$ YR^{-1} FROM 100 TO 10,000 YRS

The individual entries in this table correspond to computational scenarios of the form $S(\mathbf{n})$. For a specified number of intrusions, the first column indicates the time interval in which the first intrusion occurs, the second column indicates the time interval in which the second intrusion occurs, and so on, where 1 ~ [0, 2000], 2 ~ [2000, 4000], 3 ~ [4000, 6000], 4 ~ [6000, 8000], and 5 ~ [8000, 10000]; the last column lists the probability for each combination of intrusions calculated with the relationship in Eq. 3-28.

0 Intrusions
(prob = 3.888×10^{-2})
(cum prob = 3.888×10^{-2})
(comp scen = 1)

1 Intrusion
(prob = 1.263×10^{-1})
(cum prob = 1.651×10^{-1})
(comp scen = 5)

I_1	I_2	I_3	I_4	Prob
1				2.423×10^{-2}
2				2.551×10^{-2}
3				2.551×10^{-2}
4				2.551×10^{-2}
5				2.551×10^{-2}
				1.263×10^{-1}

2 Intrusions
(prob = 2.050×10^{-1})
(cum prob = 3.701×10^{-1})
(comp scen = 15)

I_1	I_2	I_3	I_4	Prob
1	1			7.551×10^{-3}
1	2			1.590×10^{-2}
1	3			1.590×10^{-2}
1	4			1.590×10^{-2}
1	5			1.590×10^{-2}
2	2			8.366×10^{-3}
2	3			1.673×10^{-2}
2	4			1.673×10^{-2}
2	5			1.673×10^{-2}
3	3			8.366×10^{-3}
3	4			1.673×10^{-2}
3	5			1.673×10^{-2}
4	4			8.366×10^{-3}
4	5			1.673×10^{-2}
5	5			8.366×10^{-3}
				2.050×10^{-1}

3 Intrusions
(prob = 2.219×10^{-1})
(cum prob = 5.920×10^{-1})
(comp scen = 35)

I_1	I_2	I_3	I_4	Prob
1	1	1		1.569×10^{-3}
1	1	2		4.953×10^{-3}
1	1	3		4.953×10^{-3}
1	1	4		4.953×10^{-3}
1	1	5		4.953×10^{-3}
1	2	2		5.214×10^{-3}
1	2	3		1.043×10^{-2}
1	2	4		1.043×10^{-2}
1	2	5		1.043×10^{-2}
1	3	3		5.214×10^{-3}
1	3	4		1.043×10^{-2}
1	3	5		1.043×10^{-2}
1	4	4		5.214×10^{-3}
1	4	5		1.043×10^{-2}
1	5	5		5.214×10^{-3}
2	2	2		1.829×10^{-3}
2	2	3		5.488×10^{-3}
2	2	4		5.488×10^{-3}
2	2	5		5.488×10^{-3}
2	3	3		5.488×10^{-3}
2	3	4		1.098×10^{-2}
2	3	5		1.098×10^{-2}
2	4	4		5.488×10^{-3}
2	4	5		1.098×10^{-2}
2	5	5		5.488×10^{-3}
3	3	3		1.829×10^{-3}
3	3	4		5.488×10^{-3}
3	3	5		5.488×10^{-3}
3	4	4		5.488×10^{-3}
3	4	5		1.098×10^{-2}
3	5	5		5.488×10^{-3}
4	4	4		1.829×10^{-3}
4	4	5		5.488×10^{-3}
4	5	5		5.488×10^{-3}
5	5	5		1.829×10^{-3}
				2.219×10^{-1}

4 Intrusions
(prob = 1.801×10^{-1})
(cum prob = 7.722×10^{-1})
(comp scen = 70)

I_1	I_2	I_3	I_4	Prob
1	1	1	1	2.444×10^{-4}
1	1	1	2	1.029×10^{-3}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
1	2	3	4	6.841×10^{-3}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
4	5	5	5	1.200×10^{-3}
5	5	5	5	3.000×10^{-4}
				1.801×10^{-1}

5 Intrusions
(prob = 1.170×10^{-1})
(cum prob = 8.891×10^{-1})
(comp scen = 126)

6 Intrusions
(prob = 6.331×10^{-2})
(cum prob = 9.525×10^{-1})
(comp scen = 210)

7 Intrusions
(prob = 2.937×10^{-2})
(cum prob = 9.818×10^{-1})
(comp scen = 330)

TABLE 3-2. PROBABILITIES FOR COMBINATIONS OF INTRUSIONS OVER 10,000 YRS FOR $\lambda = 0$ FROM 0 TO 100 YRS, $\lambda = 3.28 \times 10^{-4}$ YR^{-1} FROM 100 TO 10,000 YRS (concluded)

8 Intrusions	11 Intrusions	14 Intrusions
(prob = 1.192×10^{-2})	(prob = 4.123×10^{-4})	(prob = 6.464×10^{-6})
(cum prob = 9.937×10^{-1})	(cum prob = 9.999×10^{-1})	(cum prob =)
(comp scen = 495)	(comp scen = 1365)	(comp scen = 3060)
9 Intrusions	12 Intrusions	15 Intrusions
(prob = 4.301×10^{-3})	(prob = 1.116×10^{-4})	(prob = 1.399×10^{-6})
(cum prob = 9.980×10^{-1})	(cum prob =)	(cum prob =)
(comp scen = 715)	(comp scen = 1820)	(comp scen = 3876)
10 Intrusions	13 Intrusions	
(prob = 1.397×10^{-3})	(prob = 2.787×10^{-5})	
(cum prob = 9.994×10^{-1})	(cum prob =)	
(comp scen = 1001)	(comp scen = 2380)	

An important point to bear in mind is that calculations to obtain cS_i are performed at the level of the individual time histories contained in the set S shown in Equation 3-11. For this reason, the computational scenarios S_i used in the construction of CCDFs should be reasonably "homogeneous"; otherwise, it is not possible to assume that a calculation performed for a specific time history in S_i is a reasonable surrogate for the calculations that might be performed for all the other time histories in S_i. However, calculations are performed at the level of individual time histories regardless of whether the previously discussed summary or computational scenarios are under consideration.

In what follows, a summary description of the models being used in the WIPP performance assessment will be given. Then, the way in which calculations are organized to provide results for comparison with the EPA release limits will be described.

3.4.1 OVERVIEW OF MODELS

The models used in the WIPP performance assessment, or any other complex analysis, actually exist at four different levels. First, there are conceptual models that characterize our perception of the site. These models provide a nonmathematical summary of our knowledge of the site and the physical processes that operate there. Development of an appropriate conceptual model, or site description as it is sometimes called, is an important part of the WIPP performance assessment. Summaries of the current conceptual model for the WIPP are given in Chapter 5 of this volume. An adequate conceptual model is essential both for the development of the sample space S appearing in Equation 3-11 and the division of the sample space into the scenarios S_i appearing in Equation 3-1.

Second, mathematical models are developed to represent the processes at the site. The conceptual models provide the context within which these mathematical models must operate and indicate the processes that they must characterize. The mathematical models are predictive in the sense that, given known properties of the system and possible perturbations to the system, they project the response of the system. The processes that are represented by these mathematical models include fluid flow, heat flow, mechanical deformation, radionuclide transport by groundwater, removal of waste by intruding boreholes, and human exposure to radionuclides released to the surface environment. Among the dependent variables predicted by these models are pressurization of the repository by gas generation, deformation of the repository due to salt creep, removal of radionuclides from the repository due to the inflow and subsequent outflow of brine, release of radionuclides to the accessible environment due to either radionuclide transport in the Culebra or cuttings removal to the surface, and human exposure to radionuclides brought to the surface. Mathematical models are often systems of ordinary or partial differential equations. However, other possibilities exist. A description of the mathematical models being used in the WIPP performance assessment is given in Volume 2, Chapters 4 through 7 of this report.

Third, numerical models are developed to approximate the mathematical models. Most mathematical models do not have closed-form solutions. Simply put, it is not possible to find simple functions that equal the solutions of the equations in the model. As a result, numerical procedures must be developed to provide approximations to the solutions of the mathematical models. In essence, these approximations provide "numerical models" that calculate results that are close to the solutions of the original mathematical models. For example, Runge-Kutta procedures are often used to solve ordinary differential equations, and finite difference and finite element methods are used to solve partial differential equations. In practice, it is unusual for a mathematical model to have a solution that can be determined without the use of an intermediate numerical model. A brief description of the numerical models being used in the WIPP performance assessment is given in Volume 2, Chapters 4 through 7 of this report.

Fourth, computer models must be used to implement the numerical models. It is unusual for a mathematical model and its associated numerical model to be sufficiently simple to permit a "pencil-and-paper" solution. Thus, computer programs must be developed that will carry out the actual calculations. These computer models are often quite general in the sense that the user exercises a large amount of control over both the mathematical model and its numerical solution through the specific inputs supplied to the computer model. Indeed, most computer models have the capability to implement a variety of mathematical and numerical models. The computer model is where the conceptual model, mathematical model, numerical model, and analyst come together to produce predicted results.

It is the computer models that actually predict the consequences cS_i appearing in Equation 3-1. Further, several models are often used in a single analysis, with individual models both receiving input from a preceding model and producing output that is then used as input to another model. Figure 3-15 illustrates the sequence of linked models that was used in the 1991 WIPP performance assessment. Each of the models appearing in this figure is briefly described in Table 3-3; more information is available in Volume 2, Chapters 4 through 7 of this report and the model descriptions for the individual programs.

3.4.2 ORGANIZATION OF CALCULATIONS FOR PERFORMANCE ASSESSMENT

As shown in Table 3-2, even a fairly coarse gridding on time leads to far too many computational scenarios (e.g., $S(\mathbf{n})$ and $S(\mathbf{l},\mathbf{n})$) to perform a detailed calculation for each of them. Construction of a CCDF for comparison against the EPA release limits requires the estimation of cumulative probability through at least the 0.999 level. Thus, depending on the value for the rate constant λ in the Poisson model for drilling, this may require the inclusion of computational scenarios involving as many as 10 to 12 drilling intrusions, which results in a total of several thousand computational scenarios. Further, this number does not include the effects of different activity levels in the waste. To obtain results for such a large number of computational scenarios, it is necessary to plan and implement the overall calculations very carefully. The manner in which this can be done is not unique. The following describes the approach used in the 1991 WIPP performance assessment to calculate a CCDF for comparison with the EPA release limits.

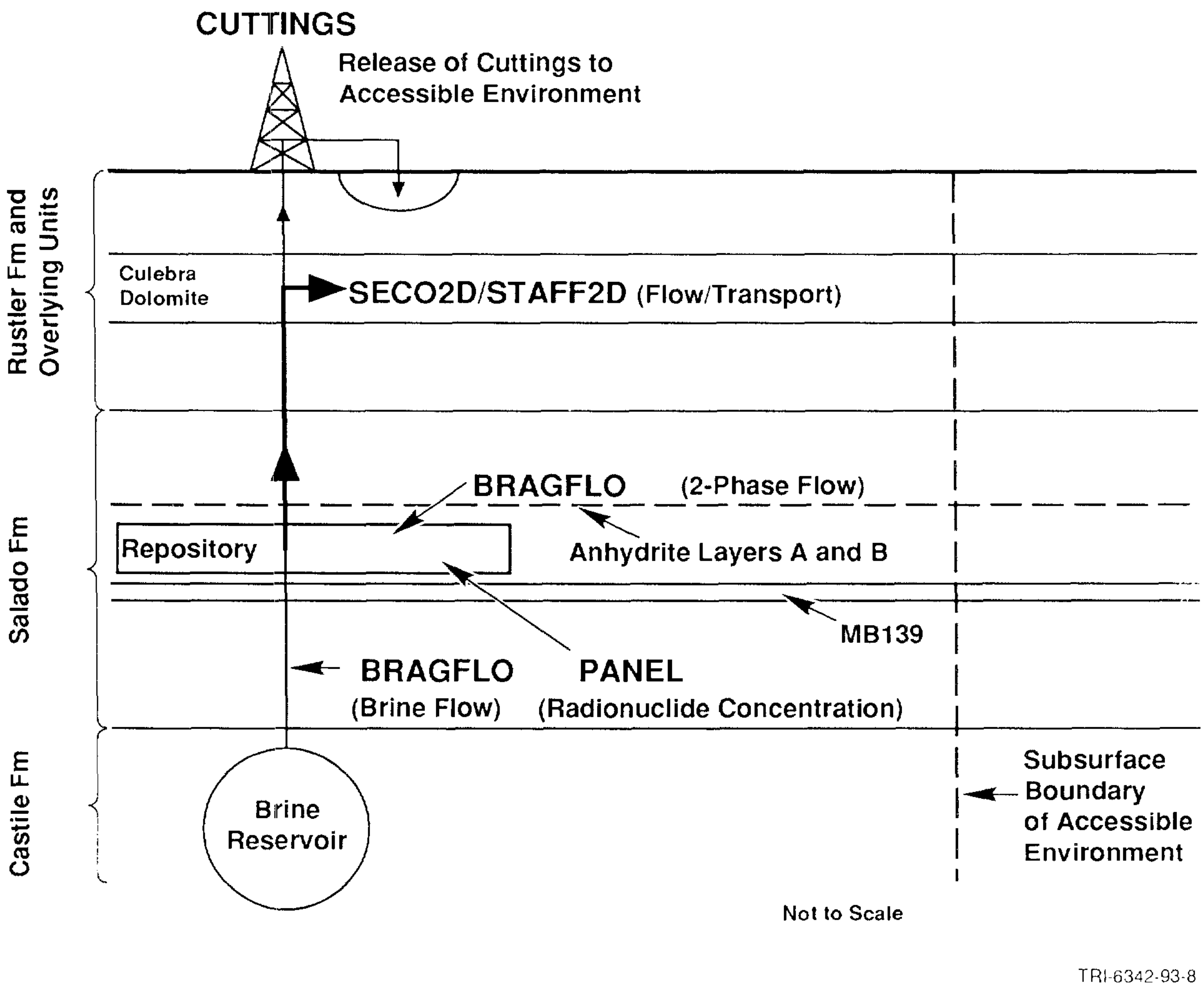

Figure 3-15. Models Used in 1991 WIPP Performance Assessment. The names for computer models (i.e., computer codes) are shown in capital letters.

TABLE 3-3. SUMMARY OF COMPUTER MODELS USED IN THE 1991 WIPP PERFORMANCE ASSESSMENT

Model	Description
CUTTINGS	Calculates the quantity of radioactive material (in curies) brought to the surface as cuttings and cavings generated by an exploratory drilling operation that penetrates a waste panel (Volume 2, Chapter 7 of this report).
BRAGFLO	Describes the multiphase flow of gas and brine through a porous, heterogenous reservoir. BRAGFLO solves simultaneously the coupled partial differential equations that describe the mass conservation of gas and brine along with appropriate constraint equations, initial conditions, and boundary conditions (Volume 2, Chapter 5 of this report).
PANEL	Calculates rate of discharge and cumulative discharge of radionuclides from a repository panel through an intrusion borehole. Discharge is a function of fluid flow rate, nuclide solubility, and remaining inventory (Volume 2, Chapter 5 of this report).
SECO2D	Calculates single-phase Darcy flow for groundwater flow problems in two dimensions. The formulation is based on a single partial differential equation for hydraulic head using fully implicit time differencing (Volume 2, Chapter 6 of this report).
STAFF2D	Simulates fluid flow and transport of radionuclides in fractured porous media. STAFF2D is a two-dimensional finite element code (Huyakorn et al., 1989; Volume 2, Chapter 6 of this report).

As indicated in Equation 3-21, the 10,000-yr time interval that must be considered for comparison with the EPA release limits can be divided into disjoint subintervals $[t_{i-1}, t_i]$, $i = 1, 2, \ldots, nT$, where nT is the number of time intervals selected for use. The following results can be calculated for each time interval:

rC_i = EPA normalized release to the surface environment for cuttings removal due to a single borehole in time interval i with the assumption that the waste is homogeneous (i.e., waste of different activity levels is not present), (3-30)

rC_{ij} = EPA normalized release to the surface environment for cuttings removal due to a single borehole in time interval i that penetrates waste of activity level j, (3-31)

$rGW1_i$ = EPA normalized release to the accessible environment for groundwater transport initiated by a single borehole in time interval i, (3-32)

and

$rGW2_i$ = EPA normalized release to the accessible environment for groundwater transport initiated by two boreholes in the same waste panel in time interval i, of which one penetrates a pressurized brine pocket and one does not (i.e., an E1E2-type scenario). (3-33)

In general, rC_i, rC_{ij}, $rGW1_i$, and $rGW2_i$ will be vectors containing a large variety of information; however, for notational simplicity, a vector representation will not be used. For the WIPP performance assessment, the cuttings release to the accessible environment (i.e., rC_i and rC_{ij}) is determined by the CUTTINGS program, and the groundwater release to the accessible environment (i.e., $rGW1_i$ and $rGW2_i$) is determined for the 1991 performance assessment through a sequence of linked calculations involving the BRAGFLO, PANEL, SECO2D, and STAFF2D programs.

The releases rC_i, rC_{ij}, $rGW1_i$ and $rGW2_i$ are used to construct the releases associated with the many individual computational scenarios that are used in the construction of a CCDF for comparison with the EPA release limits. The following assumptions are made:

(1) With the exception of E1E2-type scenarios, no synergistic effects result from multiple boreholes, and thus, the total release for a scenario involving multiple intrusions can be obtained by adding the releases associated with the individual intrusions.

(2) An E1E2-type scenario can only take place when the necessary boreholes occur within the same time interval $[t_{i-1}, t_i]$.

(3) An E1E2-type scenario involving more than two boreholes will have the same release as an E1E2-type scenario involving exactly two boreholes.

The preceding assumptions are used to construct the releases for individual computational scenarios.

The normalized releases rC_i, rC_{ij} and $rGW1_i$ can be used to construct the EPA normalized releases for the scenarios $S(\mathbf{n})$ and $S(\mathbf{l},\mathbf{n})$ defined in Equations 3-22 and 3-25, respectively. For $S(\mathbf{n})$, the normalized release to the accessible environment can be approximated by

$$cS(\mathbf{n}) = \sum_{j=1}^{nBH} (rC_{m(j)} + rGW1_{m(j)}), \tag{3-34}$$

where m(j) designates the time interval in which the j^{th} borehole occurs. The vector

$$\mathbf{m} = [m(1), m(2), \ldots, m(nBH)] \tag{3-35}$$

is uniquely determined once the vector **n** appearing in the definition of $S(\mathbf{n})$ is specified. The definition of $S(\mathbf{n})$ contains no information on the activity levels encountered by the individual boreholes, and so $cS(\mathbf{n})$ was constructed with the assumption that all waste is of the same average activity. However, the definition of $S(\mathbf{l},\mathbf{n})$ does contain information on activity levels, and the associated normalized release to the accessible environment can be approximated by

$$cS(\mathbf{l},\mathbf{n}) = \sum_{j=1}^{nBH} \left[rC_{m(j),\ell(j)} + rGW1_{m(j)} \right], \tag{3-36}$$

which does incorporate the activity levels encountered by the individual boreholes. The normalized releases for the computational scenarios $S^{+-}(t_{i-1}, t_i)$ and $S^{+-}(\mathbf{l}; t_{i-1}, t_i)$ defined in Equations 3-23 and 3-26, respectively, can be constructed in a similar manner.

Additional information on the procedures being used to construct CCDFs for the 1991 WIPP performance assessment is given in Volume 2, Chapter 3 of this report.

3.5 Uncertainty and Sensitivity Analysis

The performance of uncertainty and sensitivity analyses is an important part of the WIPP performance assessment. The need to conduct such analyses has a large effect on the overall structure of the WIPP performance assessment. In the context of this report, uncertainty analysis involves determining the uncertainty in model predictions that results from imprecisely known input variables, and sensitivity analysis involves determining the contribution of individual input variables to the uncertainty in model predictions. Specifically, uncertainty and sensitivity analyses involve the study of the effects of subjective, or type B, uncertainty. As previously discussed, the effects of stochastic, or type A, uncertainty is incorporated into the WIPP performance assessment through the scenario probabilities pS_i appearing in Equation 3-1. However, it is possible to have subjective uncertainty in quantities used in the characterization of stochastic uncertainty.

3.5.1 AVAILABLE TECHNIQUES

Review of Techniques

Four basic approaches to uncertainty and sensitivity analysis have been developed: differential analysis, Monte Carlo analysis, response surface methodology, and Fourier amplitude sensitivity test. This section provides a brief overview of these approaches and references to more detailed sources of information.

Differential analysis is based on using a Taylor series to approximate the model under consideration. Once constructed, this series is used as a surrogate for the original model in uncertainty and sensitivity studies. A differential analysis involves four steps: (1) selection of base-case values, ranges, and distributions for the input variables under consideration; (2) development of a Taylor series approximation to the original model; (3) assessment of uncertainty in model predictions through the use of variance propagation techniques with the Taylor series approximation to the model; and (4) determination of the sensitivity of model predictions to model input on the basis of fractional contributions to variance. The most demanding part of a differential analysis is often the calculation of the partial derivatives used in the Taylor series constructed in the second step. Additional sources of information on differential analysis are given in Table 3-4.

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 independent variables that give rise to this uncertainty. A Monte Carlo analysis involves five steps: (1) selection of a range and distribution for each input variable; (2) generation of a sample from the ranges and distributions assigned to the input variables; (3) evaluation of the model for each element of the sample; (4) assessment of the uncertainty in model predictions through the use of estimated means, variances, and distribution functions; and (5) determination of the sensitivity of model predictions to model input on the basis of scatterplots, regression analysis, and correlation analysis. Additional sources of information on Monte Carlo analysis are given in Table 3-4.

Response surface methodology is based on developing a response surface approximation to the model under consideration. This approximation is then used as a surrogate for the original model in subsequent uncertainty and sensitivity analyses. An analysis based on response surface methodology involves six steps: (1) selection of a range and distribution for each input variable; (2) development of an experimental design that defines the combinations of variable values for which model evaluations will be performed; (3) evaluation of the model for each point in the experimental design; (4) construction of a response surface approximation to the original model on the basis of the model evaluations obtained in the preceding step; (5) assessment of the uncertainty in model predictions through the use of either variance propagation techniques or Monte Carlo simulation with the previously constructed response surface; and (6) determination of the sensitivity of model predictions to model input on the basis of fractional contribution to variance. Addition sources of information on response surface methodology are given in Table 3-4.

The Fourier amplitude sensitivity test (FAST) is based on performing a numerical calculation to obtain the expected value and variance of a model prediction. The basis of this calculation is a transformation that converts a multidimensional integral over all the uncertain model inputs to a one-dimensional integral. Further, a decomposition of the Fourier series representation of the model is used to obtain the fractional contribution of the individual input variables to the variance of the model prediction. An analysis based on the FAST approach involves four steps: (1) selection of a range and distribution for each input variable; (2) development of a transformation that converts the multidimensional integrals required to calculate the expected value and variance of a model prediction to one-dimensional integrals; (3) assessment of the uncertainty in model predictions by evaluation of the one-dimensional integrals constructed in the preceding step to obtain expected values and variances; and (4) determination of the sensitivity of model predictions to model inputs on the basis of fractional contributions to variance obtained from a decomposition of a Fourier series representation for the model. Additional sources of information on the FAST approach are given in Table 3-4.

Relative Merits of Individual Techniques

Differential analysis is based on developing a Taylor series approximation to the model under consideration. Ultimately, the quality of the analysis results will depend on how well this series approximates the original model. Desirable properties of differential analysis include the following: (1) the effects of small perturbations away from the base-case value about which the Taylor series was developed are revealed; (2) uncertainty and sensitivity analyses are straightforward once the Taylor series is developed; (3) specialized techniques (e.g., adjoint, Green's function, GRESS/ADGEN) exist to facilitate the calculation of derivatives; and (4) the approach has been widely studied and applied.

However, there are two important drawbacks to differential analysis that should always be considered when selecting the procedure to be used in an

TABLE 3-4. SOURCES OF ADDITIONAL INFORMATION ON UNCERTAINTY AND SENSITIVITY ANALYSIS

Topic	References
Differential Analysis	Ronen, 1988; Lewins and Becker, 1982; Frank, 1978; Dickinson and Gelinas, 1976; Tomovic and Vukobratovic, 1972; Cacuci, 1981a,b; Cacuci et al., 1980; Dougherty and Rabitz, 1979; Dougherty et al., 1979; Hwang et al., 1978; Oblow et al., 1986; Pin et al., 1986; Worley and Horwedel, 1986; Oblow, 1985
Monte Carlo Analysis	Helton et al., 1986; Helton et al., 1985; Hendry, 1984; Fedra, 1983; Gardner and O'Neill, 1983; Iman and Conover, 1982a; Iman and Conover, 1980a,b; Iman et al., 1981a; Iman et al., 1981b; Schwarz and Hoffman, 1980; Iman et al., 1978
Response Surface Methodology	Box and Draper, 1987; Kleijnen, 1987; Myers, 1971; Olivi, 1986; Morton, 1983; Mead and Pike, 1975; Kleijnen, 1974
Fourier Amplitude Sensitivity Test	Liepmann and Stephanopoulos, 1985; McRae et al., 1981; Cukier et al., 1978; Cukier et al., 1973; Schaibly and Shuler, 1973
Reviews	Helton et al., 1991; Wu et al., 1991; Zimmerman et al., 1990; Doctor, 1989; Bonano and Cranwell, 1988; NEA, 1987; Rish and Marnicio, 1988; Fischer and Ehrhardt, 1985; Iman and Helton, 1985a; Hendrickson, 1984; Rabitz et al., 1983; Cox and Baybutt, 1981; Rose and Swartzman, 1981; Tilden et al., 1981; Mazumdar et al., 1978; Mazumdar et al., 1976; Mazumdar et al., 1975
Comparative Studies	Kim et al., 1988a,b; Mishra and Parker, 1989; Doctor et al., 1988; Iman and Helton, 1988; Maerker, 1988; Seaholm et al., 1988; Sykes and Thomson, 1988; Obray et al., 1986; Downing et al., 1985; Iman and Helton, 1985b; Jacobson et al., 1985; Uliasz, 1985; Harper and Gupta, 1983; Montgomery et al., 1983; Rose, 1982; Ahmed et al., 1981; Gardner et al., 1981; Scavia et al., 1981; Cox, 1977; Burns, 1975

uncertainty/sensitivity study. First, differential analysis is inherently local. The farther a perturbation moves from the base-case value about which the Taylor series was constructed, the less reliable the analysis results become. In particular, differential analysis is a poor choice for use in estimating distribution functions and provides no information on the possible existence of thresholds or discontinuities in the relationships between independent and dependent variables. Overall, the more nonlinear the relationships between the independent and dependent variables, the more difficult it is to employ a differential analysis effectively. Second, differential analyses can be very difficult to implement and often require large amounts of human and/or computer time. This difficulty arises from the need to calculate the partial derivatives required in the Taylor series. The possible use of sophisticated techniques such as the GRESS/ADGEN procedures offers some encouragement in this area. Even so, the need to calculate the required derivatives should not be taken lightly.

Monte Carlo analysis is based on the use of a probabilistic procedure to select model input. Then, uncertainty analysis results are obtained directly from model predictions without the use of an intermediate surrogate model, and sensitivity analysis results are obtained by exploring the mapping from model input to model predictions that formed the basis for the uncertainty analysis. Desirable properties of Monte Carlo analysis include the following: (1) the full range of each input variable is sampled and subsequently used as model input; (2) uncertainty results are obtained without the use of a surrogate model; (3) extensive modifications to the original model are not necessary (such modifications are often required when adjoint or Green's function techniques are used as part of a differential analysis); (4) the full stratification over the range of each input variable facilitates the identification of nonlinearities, thresholds, and discontinuities; (5) a variety of regression-based sensitivity analysis techniques are available; and (6) the approach is conceptually simple, widely used, and easy to explain.

Two particularly appealing features of Monte Carlo analysis are the full coverage of the range of each input variable and the ease with which an analysis can be implemented. The first feature is particularly important when the input variables have large ranges and the existence of nonlinear relationships between the input and output variables is a possibility. With respect to the second feature, essentially any variable that can be supplied as an input or generated as an output can be included in a Monte Carlo analysis without any modification to the original model.

The major drawback to Monte Carlo procedures is the fact that multiple model evaluations are required. If the model is computationally expensive to evaluate or many model evaluations are required, then the cost of the required calculations may be large. Computational cost should always be considered when selecting a technique, but it is rarely the dominant cost in performing an analysis. Special techniques such as Latin hypercube sampling and importance sampling can often be used to reduce the number of required model evaluations without compromising the overall quality of an analysis. Further, it is important to recognize that, in practice, the other analysis techniques discussed in this section can require as much computational time as Monte Carlo analysis.

Response surface methodology is based on constructing a response-surface approximation to the original model. This approximation is then used as a surrogate for the original model in subsequent uncertainty and sensitivity studies. Desirable properties of response-surface methodology include the following: (1) complete control over the structure of model input through the experimental design selected for use; (2) near optimum choice for a model whose predictions are known to be a linear or quadratic function of the input variables; and (3) uncertainty and sensitivity analyses that are inexpensive and straightforward once the necessary response surface approximation has been constructed. Further, the development of experimental designs has been widely studied, although typically for situations that are considerably less involved than those encountered in performing an uncertainty/sensitivity study for a complex model.

There are also several drawbacks to response surface methodology that should be considered when an approach to uncertainty/sensitivity analysis is being selected. These include the following: (1) difficulty in development of an appropriate experimental design because of many input variables, many output variables, unknown form for the model, or spatial/temporal variability; (2) use of few values for each input variable; (3) possible requirement of many design points; (4) difficulties in detecting thresholds, discontinuities, and nonlinearities; (5) difficulties in including correlations and restrictions between input variables; and (6) difficulty in construction of an appropriate response-surface approximation to the original model, which may require a considerable amount of statistical sophistication and/or artistry. Ultimately, the final uncertainty/ sensitivity results are no better than the response-surface approximation to the original model. Response-surface methodology will work when there are only a few (typically, less than 10) input variables, a limited number of distinct output variables (because a design that is appropriate for one output variable may not be appropriate for a different output variable), and the relationships between the input and output variables are basically linear or quadratic or involve a few cross-products. Otherwise, the structure of the input-output relationships is too complicated to be captured by a classical experimental design (or a sequence of designs if a sequential approach is being used) in an efficient manner.

The FAST approach is based on performing a numerical calculation to estimate expected value and variance. Further, sensitivity results are obtained by decomposing the variance estimate into the variances due to the individual input variables. Desirable properties of the FAST approach include the following: (1) full range of each input variable is covered; (2) estimation of expected value and variance is by a direct calculation rather than by use of a surrogate model; and (3) modifications to the original model are not required.

There are also several drawbacks to using the FAST approach. These include the following: (1) the underlying mathematics is complicated and difficult to explain; (2) the approach is not widely known or used; (3) developing the necessary space-filling curve and performing the numerical integration over this curve to obtain expected value and variance is complicated; (4) many model evaluations may be required; (5) an estimate for the cumulative distribution function of the dependent variable is not provided; and (6) it is not possible to specify correlations or other types of restrictions between variables. Fortunately, software has been developed to facilitate the implementation of an uncertainty/sensitivity study based on the FAST approach (McRae et al., 1981). As analyses are currently performed with the FAST approach, no information on discontinuities, thresholds, or nonlinearities is obtained. However, it is probably possible to investigate this type of behavior with the model evaluations that must be performed in the numerical integrations to obtain expected value and variance.

Monte Carlo as a Preferred Approach

Each approach to uncertainty and sensitivity analysis has its advantages and disadvantages, and all approaches have been successfully applied. It would be a mistake to state categorically that one approach will always be superior to the others regardless of the model under consideration. For a given analysis problem, the available approaches should be considered, and the approach that seems most appropriate for the problem should be selected. This selection should take into account the nature of the model, the type of uncertainty and sensitivity analysis results desired, the cost of modifying and/or evaluating the model, the human cost associated with mastering and implementing a technique, the time period over which an analysis must be performed, and the programmatic risk associated with unanticipated complications in the implementation of a technique.

The comments of the preceding paragraph notwithstanding, it is felt that Monte Carlo techniques provide the best overall approach for studying problems related to performance assessment for radioactive waste disposal. This statement is made for several reasons.

First, there are often large uncertainties in such problems. Due to full stratification over the range of each variable, Monte Carlo techniques are particularly appropriate for analysis problems in which large uncertainties are associated with the input variables. In particular, differential analysis and response surface methodology are likely to perform poorly when the relationships between the input and output variables are nonlinear and the input variables have large uncertainties.

Second, Monte Carlo techniques provide direct estimates for distribution functions. Neither differential analysis nor the FAST approach is intended for the estimation of distribution functions. The estimates obtained with response surface methodology are no better than the response surface approximation to the original model. It should be possible to estimate distribution functions with results generated as part of the FAST approach, but this possibility apparently has not been investigated and applied.

Third, Monte Carlo techniques do not require a large amount of sophistication that goes beyond the analysis problem of interest. In contrast, differential analysis, response surface methodology, and the FAST approach require a large amount of specialized knowledge to make them work. Developing this knowledge and making these techniques work can be very costly in terms of analyst time. Conceptually, Monte Carlo techniques are simpler and do not require modifications to the original model or additional numerical procedures. For example, both differential analysis and the FAST approach can require sophisticated numerical calculations. The application of response surface methodology can require specialized knowledge in experimental design and response surface construction. As a result, analyses based on Monte Carlo techniques are usually easier to present and explain than analyses based on the other techniques.

Fourth, Monte Carlo techniques 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 radioactive waste disposal sites (Bonano et al., 1989; Cranwell et al., 1987) and probabilistic risk assessments for nuclear power plants (U.S. NRC, 1990; Helton et al., 1988; draft of NUREG/CR-4551, U.S. NRC). Due to the use of a number of independent computer programs and the necessity to handle information at model interfaces appropriately, the other methods do not seem to be applicable to this type of analysis.

Fifth, Monte Carlo techniques create a mapping from analysis input to analysis results. This mapping 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. Differential analysis is inherently local. Response surface methodology employs a very sparse stratification. The exact nature of the mapping produced by the FAST approach has not been investigated.

3.5.2 MONTE CARLO ANALYSIS

As previously discussed, the WIPP performance assessment uses Monte Carlo techniques to study the impact of uncertainties. A Monte Carlo analysis involves five steps. Each of these steps is now discussed in the context of the WIPP performance assessment.

Selection of Variable Ranges and Distributions

Monte Carlo analyses use a probabilistic procedure for the selection of model input. Therefore, the first step in a Monte Carlo analysis is the selection of ranges and distributions for the variables under consideration. When performed carefully, this can be the largest and most expensive part of a Monte Carlo analysis. However, the amount of effort expended here depends strongly on the purpose of the analysis.

If the analysis is primarily exploratory, then rather crude characterizations of the ranges and distributions for the input variables may be adequate. For example, physical plausibility arguments might be used to establish ranges, and uniform or loguniform distributions could be assumed within these ranges. These assumptions are often adequate to bound the ranges for output variables of interest and also to determine which input variables have the greatest influence on the output variables. The estimated range for an output variable and associated sensitivity results are primarily determined by the ranges assigned to the input variables. Thus, even for exploratory studies, care should be taken to avoid assigning unreasonably large ranges to variables. Sensitivity results are generally less dependent on the actual distributions assigned to the input variables than they are to the ranges chosen for the variables. However, distributional assumptions can have a large impact on the distributions estimated for output variables. Thus, when distributions for output variables must be estimated accurately, care must be used in developing distributions for the input variables.

Resources can often be used most effectively by performing a Monte Carlo analysis in an iterative manner. In a first iteration, rather crude range and distribution assumptions can be used to determine which input variables dominate the behavior of output variables of interest. Often, most of the variation in an output variable will be caused by a relatively small subset of the input variables. Once the most important input variables are identified, resources can be concentrated on characterizing their uncertainty. This avoids spending a large effort to characterize carefully the uncertainty in variables that have little impact on the ultimate outcome of an analysis. This, in essence, is the approach used in the WIPP performance assessment, where an uncertainty/sensitivity study is performed each year to determine the importance of individual variables and thereby to provide guidance for future research (e.g., Helton et al., 1991).

The variables considered in Monte Carlo studies are typically input parameters to computer models. The individual variables x_j, $j = 1, \ldots, m$, can represent any parameter used in an analysis, including hydraulic conductivities, retardations, solubility limits, scenario probabilities, parameters in distributions, probabilistic cutoffs used to eliminate low probability scenarios, and parameters that characterize numerical calculations such as mesh sizes and error bounds. The defining characteristic of these variables is that the analysis requires a single value for each variable but it is uncertain as to what the value should be. Thus, the range assigned to each variable represents the set of possible values for that variable, and the corresponding distribution characterizes the likelihood that the appropriate value to use for this variable falls in various subsets of this range. As discussed in Section 3.1.3-Characterization of Uncertainty in Risk, this type of uncertainty corresponds to what is sometimes called Type B, or subjective, uncertainty.

It is very important that the range assigned to a variable be consistent with its usage in the computer program that implements the underlying model. In particular, the range assigned to a variable should be consistent with the scale on which the variable is used in the specific implementation of the model under consideration. A common mistake is to estimate a variable on a local scale and then to infer uncritically that the observed local variability is the same as the uncertainty in this variable on a much larger scale. This can lead to serious mis-estimates of the range for the "effective" variable value that is actually used in an analysis.

For example, a computer program might take a single value for the solubility limit of a radionuclide as input, with this single value being used throughout a room in a waste repository or perhaps even throughout the entire repository. Further, theoretical calculations or experimental results might be available for solubility limits under conditions that could occur in subregions of a room but which would be very unlikely to occur uniformly over the entire room. In this case, it would be a mistake to use the range of local results to characterize the range of solubility limits for a room or the repository since this range was developed for isolated sets of conditions that would not exist over large areas. The available information should be used in the construction of a range of "effective" solubility limits that is consistent with the use of this parameter in the particular analysis being performed. Similar situations can occur in the characterizations of hydraulic conductivities, retardations, and other variables where the scale on which data are measured is very different from the scale on which estimated variables are actually used.

The preceding discussion quite naturally leads to the following question: How should the ranges and distributions for variables be determined for use in a Monte Carlo analysis? This is a reasonable question to ask, and a hard question to answer. Clearly, the answer must depend on the goals of the analysis, the time and resources available, and the type of information that exists for use in estimating ranges and distributions.

The simplest and most desirable situation would be to have a sequence

$$e_{1j},\ e_{2j},\ \ldots,\ e_{nE,j} \qquad (3\text{-}37)$$

of independent, unbiased, normally and identically distributed estimates for a variable x_j exactly as it is used by a model in a particular analysis and by the computer program that implements this model. In this case, each e_{ij} is an estimate for the corresponding model input x_j, and the single best estimate for x_j is given by

$$\bar{x}_j = \sum_{i=1}^{nE} e_{ij}/nE. \qquad (3\text{-}38)$$

Further, the standard deviation, or standard error as it is sometimes called when population parameters are being considered, for $\bar{x}_j$ is given by

$$SD(\bar{x}_j) = \left[\sum_{i=1}^{nE} (e_{ij} - \bar{x}_j)^2\right]^{1/2} / \sqrt{nE(nE-1)}. \qquad (3\text{-}39)$$

The quantity

$$t = (\bar{x}_j - x_j)/SD(\bar{x}_j) \qquad (3\text{-}40)$$

is distributed as a t-distribution with nE-1 degrees of freedom, where x_j is the appropriate but unknown variable value for use in the analysis (Iman and Conover, 1983). The preceding expression can be rearranged algebraically to obtain

$$x_j = \bar{x}_j - t\ SD(\bar{x}_j). \qquad (3\text{-}41)$$

Thus, the t-distribution can be used to define a distribution for x_j. Further, a confidence interval (e.g., 95%, 99%) for x_j can also be obtained from the t-distribution and used to define the range of x_j. This is equivalent to excluding specified regions in the tails of the t-distribution when generating x_j from the expression in Equation 3-41. The justification for using the t-distribution as a probability distribution for an uncertain variable comes from applying Bayes' Theorem with a diffuse prior distribution for both the mean and standard deviation of the sampling process (Winkler, 1972).

As just illustrated, it may be possible to estimate the range and distribution for some variables with formal statistical procedures. Such procedures should always be used when data have been collected in an appropriate manner. Appropriate data collection usually requires prior knowledge of the precise variable to be estimated and use of a carefully planned experimental design. The exact statistical procedures selected for use would depend on the experimental design and the assumed relationships between the variable to be estimated and the data from the design.

Unfortunately, most parameters used in a performance assessment are not amenable to direct statistical estimation for various subsets for the following reasons: (1) The time scales over which parameters can be estimated are often much shorter than the time scales over which they will actually be used. (2) The physical scale on which parameters can be observed is often much smaller than the physical scale on which they will be used. As a result, heterogeneities in the system prevent individual observations from being used as estimates for system parameters. (3) Estimation of some parameters (e.g., distribution coefficients) requires the removal of material from the system. This removal can alter the properties of the material and thus lead to incorrect parameter estimates. (4) The exact conditions that will exist within the system (e.g., in a waste disposal room) are not known. Thus, it is not possible to design experiments to match the exact conditions for which parameter values are needed. (5) Collection of some types of data involves a degradation of the site (e.g., the drilling of boreholes). As a result, the collection of such data is necessarily limited. (6) Some data involves the occurrence of rare events (e.g., scenario probabilities). Although the geological and historical records can be searched for more information, designed experiments are not possible. (7) Some parameters are not directly measurable. For example, the time scales associated with future human activities make it impossible to design experiments to estimate parameters (e.g., drilling rates) associated with such activities.

Due to reasons of the type outlined in the preceding paragraph, ranges and distributions for most parameters used in a performance assessment cannot be obtained by formal statistical procedures. Nonetheless, there is still a large body of relevant information that can be used in estimating ranges and distributions. Much of this information is field data collected at the site. Other sources of information include theoretical calculations, mechanistic code calculations, physical data from other sites, and knowledge of the differences between the conditions under which data were collected and the conditions under which estimated parameters are to be used.

The challenge in developing ranges and distributions for use in a Monte Carlo study is to incorporate this diverse body of information meaningfully. Indeed, the importance of such ranges and distributions is that they provide a mathematical structure that summarizes the available information in a form that can be used in further analyses. In many situations, the only practical way to develop these summary ranges and distributions is through an expert review process.

The ultimate outcome of this review process would be a distribution function F(x) of the form shown in Figure 3-16 for each independent variable of interest. For a particular variable x_j, the function F is defined such that

$$\text{prob}(x < x_j \leq x + \Delta x) = F(x + \Delta x) - F(x). \qquad (3\text{-}42)$$

That is, $F(x+\Delta x) - F(x)$ is equal to the probability that the appropriate value to use for x_j in the particular analysis under consideration falls between x and $x + \Delta x$. In most cases, the probabilities involved in this representation will be subjective in the sense that they represent a degree of belief as to where the appropriate value for x_j falls conditional on all the information available to the reviewer or reviewers. However, when formal statistical procedures can be used as is indicated in conjunction with Equation 3-41, the final result will again be a distribution of the form shown in Figure 3-16. In both cases, the data summary process will have arrived at the same place: a distribution based on available information that characterizes where the appropriate value for x_j is likely to be located.

In many situations, the most appropriate way to construct a subjective distribution of the form shown in Figure 3-16 is through the estimation of quantiles. For example, the process might start by determining minimum and maximum values for x_j, which defines the 0.00 and 1.00 quantiles. This provides estimates for the points

$$(x_{0.00}, 0.00) \text{ and } (x_{1.00}, 1.00) \qquad (3\text{-}43)$$

on the distribution function in Figure 3-16. The next point to estimate might be the median, which divides the range of x_j into two intervals of

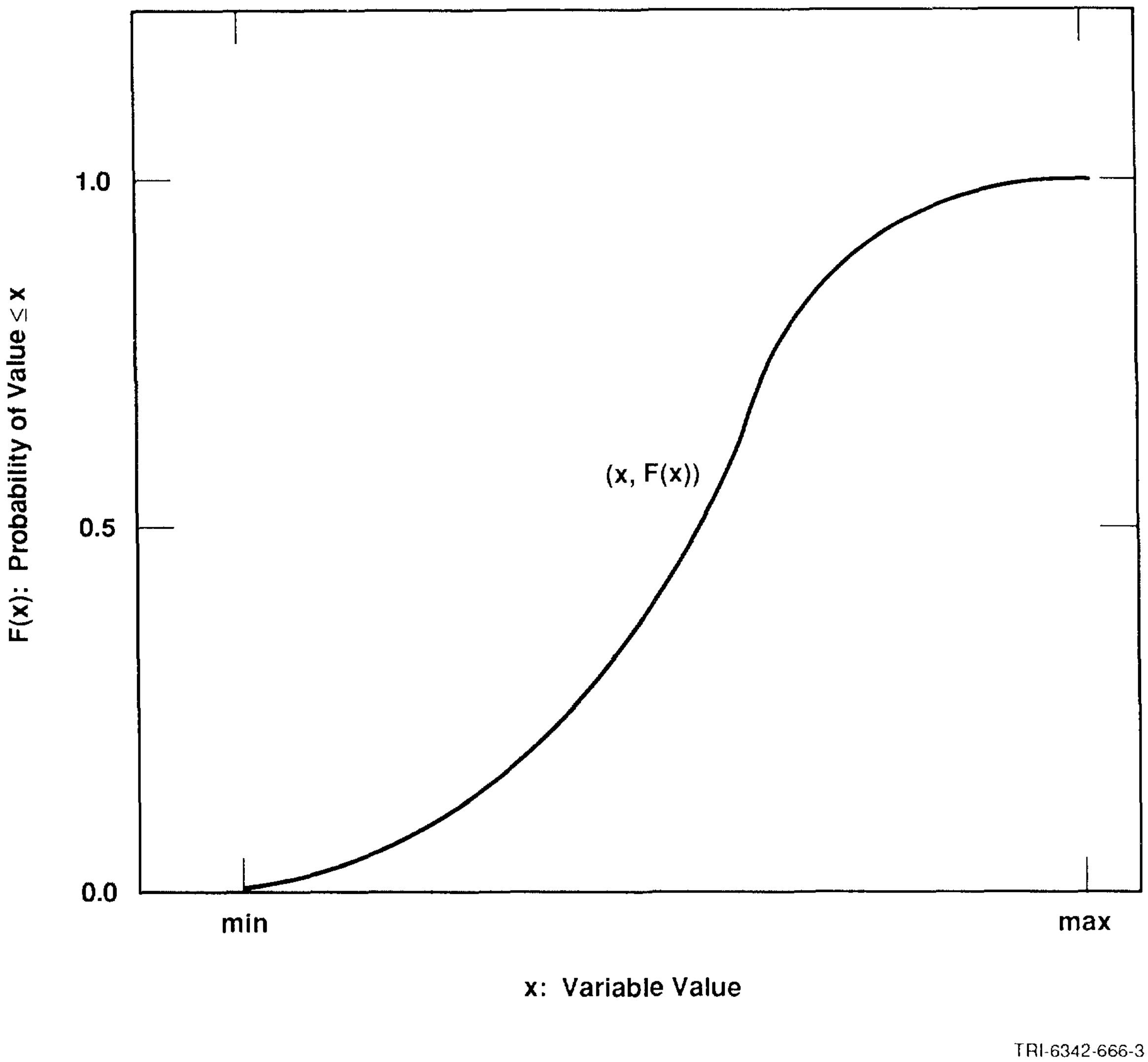

Figure 3-16. Distribution Function for an Imprecisely Known Analysis Variable. For each value x on the abscissa, the corresponding value F(x) on the ordinate is the probability that the appropriate value to use in the analysis is less than or equal to x (Helton et al., 1991).

equal probability, followed by estimates for the 0.25 and 0.75 quantiles. This produces the following additional points on the distribution function:

$$(x_{0.25}, 0.25), (x_{0.50}, 0.50), (x_{0.75}, 0.75). \tag{3-44}$$

This process would continue by estimating additional points (e.g., the 0.05, 0.10, 0.90, and 0.95 quantiles) until the shape of the distribution is reasonably characterized. The rest of the distribution could then be filled in by assuming that the distribution function is linear between the specified quantiles, which is equivalent to fitting a maximum entropy distribution (Levin and Tribus, 1978; Tierney, 1990; Cook and Unwin, 1986). Figure 3-17 illustrates what the outcome of this process might look like.

Distribution functions for imprecisely known analysis variables can also be obtained by selecting parameter values such as the mean and standard deviation for established distributions (e.g., normal, lognormal, beta). However, it is generally best to avoid this approach for several reasons.

First, there is usually no conceptual basis to pick a particular distribution. Second, it is hard to justify why a particular set of distribution parameters was selected (e.g., why a particular mean and standard deviation was selected for use with a lognormal distribution). In contrast, it is often much easier to relate the assignment of quantiles to specific information available to the reviewer. Third, most reviewers are not trained statisticians and often do not have an intuitive feeling for the relationship between the shape of a highly skewed distribution and the parameters that define it. Thus, selected parameters may not produce a distribution of the shape anticipated by the reviewer. In general, the use of formal distributions is undesirable because it puts an unnecessary transformation between the information possessed by the reviewer and the form in which this information is used in the analysis. In contrast, distributions constructed from quantiles are based on information that corresponds more closely to that available to the reviewer.

The scale of an expert review process can vary widely. At one extreme, a single individual might be involved in reviewing the available information on a particular variable and constructing the distribution shown in Figure 3-17. The actual construction of this distribution could range from being entirely subjective to using sophisticated computational procedures to relate variability in data collected at one scale to uncertainty in a parameter for use on a different scale. At the other extreme, several teams of experts could be used to estimate a distribution independently, and then the final distribution used in the analysis would be calculated by averaging the distributions obtained by the individual teams. An intermediate approach

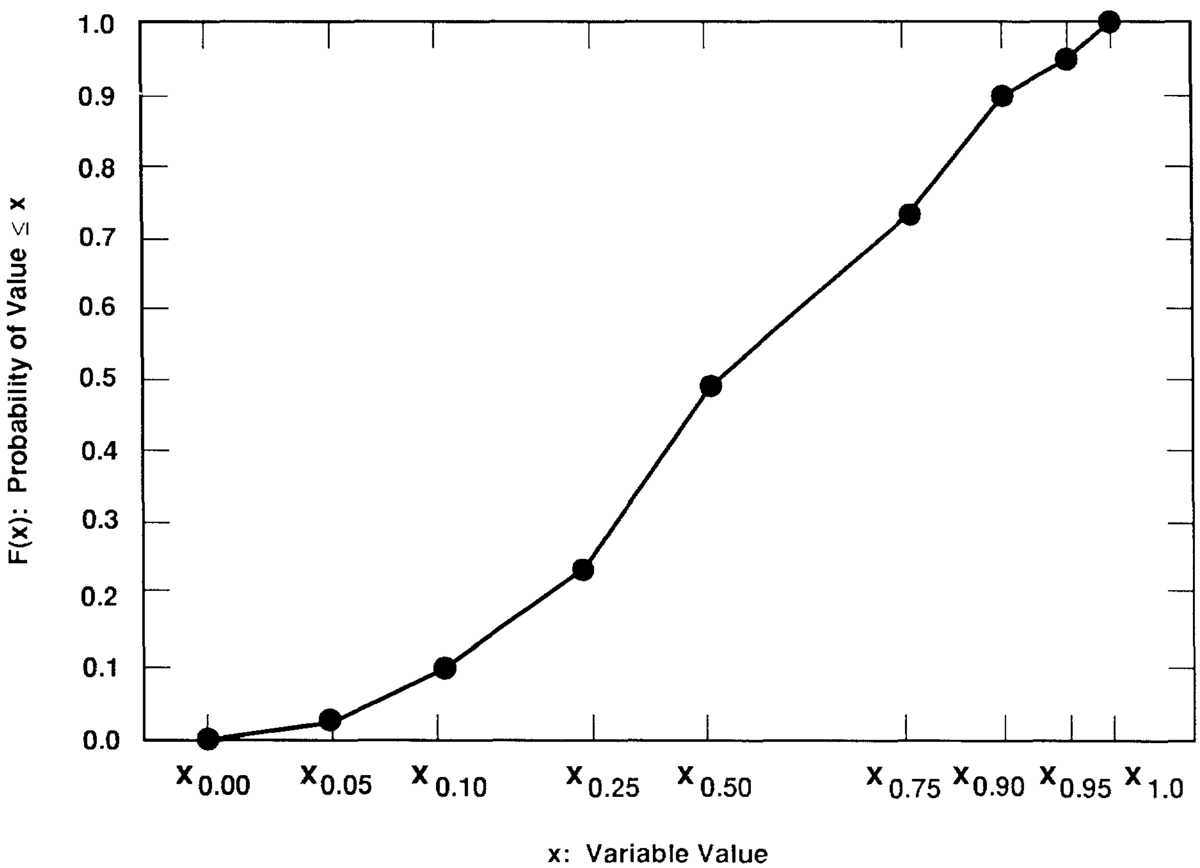

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Figure 3-17. Estimated Distribution Function for an Imprecisely Known Analysis Variable. This distribution function was built up from estimates for the following quantities: 0.00, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95 and 1.00 (Helton et al., 1991).

would be to have several knowledgeable individuals independently estimate a distribution and then average these estimates. Bonano et al. (1990) provide a detailed discussion on the elicitation and use of expert judgment in performance assessment for radioactive waste disposal.

The U.S. Nuclear Regulatory Commission's reassessment of the risk from commercial nuclear power plants (NUREG-1150) provides an excellent example of the application of a formal expert review process to develop variable ranges and distributions for use in a Monte Carlo analysis (U.S. NRC, 1990). This study involves probably the most extensive use of a formal expert review process performed to date. The general approach used and the experiences gained in its implementation are summarized in several articles (Ortiz et al., 1991; Hora and Iman, 1989). Further, the actual performance of the expert review process is summarized in a sequence of technical reports (Wheeler et al., 1989; Harper et al., 1990, 1991, and other volumes in prep.). This analysis used several experts to assess independently the range and distribution for each input variable of interest; then, the distributions supplied by the individual experts were averaged, with equal weight being given to each expert. A recent study of seismic hazard curves provides an example of the use of the team approach to estimating distributions (EPRI, 1989).

A total of 45 imprecisely known variables were selected for sampling in the 1991 WIPP performance assessment. These variables are listed in Tables 6.0-1, -2, and -3 in Volume 3 of this report. Their selection was based on their perceived importance with respect to the WIPP performance assessment and was guided in part by sensitivity studies performed in conjunction with the 1990 WIPP performance assessment (Helton et al., 1991). The distributions assigned to these variables (see Tables 6.0-1, -2, and -3 in Volume 3 of this report) characterize where a fixed, but unknown, value for a variable is likely to be located. The uncertainty in most variables was characterized internally at SNL. However, a panel of experts from outside SNL was used to assess the uncertainty in solubility limits. The deliberations of this panel are described in Volume 3, Chapter 3 of this report.

Generation of Sample

The generation of a sample from the distributions developed in the first step of a Monte Carlo analysis is now discussed. For this discussion, suppose that the multidimensional variable $\mathbf{x}$ is under consideration and that the distribution function for $\mathbf{x}$ is denoted by $F(\mathbf{x})$. Many sampling procedures have been proposed for use in Monte Carlo studies to generate samples from $F(\mathbf{x})$ (McGrath et al., 1975). The following often-used techniques are discussed below: random sampling, stratified sampling, and Latin hypercube sampling.

In random sampling, the observations

$$\mathbf{x}_i = [x_{i1}, \ldots, x_{in}], \; i = 1, \ldots, m, \tag{3-45}$$

where m is the sample size, are selected independently from the distribution defined by $F(\mathbf{x})$. In random sampling, points from different regions of the sample space of $\mathbf{x}$ occur in direct relationship to the probability of occurrence of these regions. Thus, a large sample size may be required to ensure adequate coverage of regions believed to be important but having low probabilities of occurrence.

A systematic coverage of the sample space (i.e., range) of $\mathbf{x}$ is forced in stratified sampling. Specifically, the sample space S of $\mathbf{x}$ is partitioned into nS distinct strata S_j, $j = 1, \ldots, nS$. In general each stratum has different probability p_j of occurring; that is,

$$p_j = \text{prob}(\mathbf{x} \varepsilon S_j). \tag{3-46}$$

A random sample of size m_j is then obtained from each strata S_j. That is, the points $\mathbf{x}_{jk}$, $k = 1, \ldots, m_j$, are selected at random from S_j. When all the $\mathbf{x}_{jk}$ are brought together, the result is the sequence of observations

$$\mathbf{x}_i = [x_{i1}, \ldots, x_{in}], \; i = 1, \ldots, m = \sum_{j=1}^{nS} m_j. \tag{3-47}$$

With stratified sampling, it is possible to force the selection of points from regions believed to be important even if these regions have a low probability of occurrence. This sampling technique is sometimes called importance sampling. When only one stratum is used, stratified sampling is the same as random sampling.

Stratified sampling operates to ensure the full coverage of specified regions in the sample space. This idea is carried further in Latin hypercube sampling (McKay et al., 1979) to ensure the full coverage of the range of each variable. Specifically, the range of each variable (i.e., the x_j) is divided into m intervals of equal probability and one value is selected at random from each interval. The m values thus obtained for x_1 are paired at random with the m values obtained for x_2. These m pairs are combined in a random manner with the m values of x_3 to form m triples. This process is continued until a set of m n-tuples is formed. These n-tuples are of the form

$$\mathbf{x}_i = [x_{i1}, \ldots, x_{in}], \; i = 1, \ldots, m, \tag{3-48}$$

and constitute the Latin hypercube sample. The individual x_j must be independent for the preceding construction procedure to work; a method for generating Latin hypercube and random samples from correlated variables has been developed by Iman and Conover (1982b) and will be discussed briefly.

For illustration, the results of a random sample, a stratified sample, and a Latin hypercube sample are shown in Figure 3-18. A sample of size 10 from two uniformly distributed variables is used. Ten strata are used for the stratified sample and one value is taken from each strata. The selection of strata in a stratified sample is not unique and is often made to assure that certain low probability, but high interest, subranges of the independent variables are included in an analysis.

At the end of their comparison of sampling techniques, McKay et al. (1979) conclude that Latin hypercube sampling has a number of desirable properties and recommend its consideration for use in Monte Carlo studies. These properties include (1) full stratification across the range of each variable, (2) relatively small sample sizes, (3) direct estimation of means, variances, and distribution functions, and (4) the availability of a variety of techniques for sensitivity analysis. Another desirable property of Latin hypercube sampling is that it is possible to determine the effects of different distributions for the input variables on the estimated distribution for an output variable without rerunning the model (Iman and Conover, 1980a,b). As a result of these properties, Latin hypercube sampling has become a widely used sampling technique.

Control of correlation within a sample used in a Monte Carlo analysis can be very important. If two or more variables are correlated, then it is necessary that the appropriate correlation structure be incorporated into the sample if meaningful results are to be obtained in subsequent uncertainty/ sensitivity studies. On the other hand, it is equally important that variables not appear to be correlated when they are really independent.

It is often difficult to induce a desired correlation structure on a sample. Indeed, most multivariate distributions are incompatible with the majority of correlation patterns that might be proposed for them. Thus, it is fairly common to encounter analysis situations where the proposed variable distributions and the suggested correlations between the variables are inconsistent; that is, it is not possible to have both the desired variable distributions and the requested correlations between the variables.

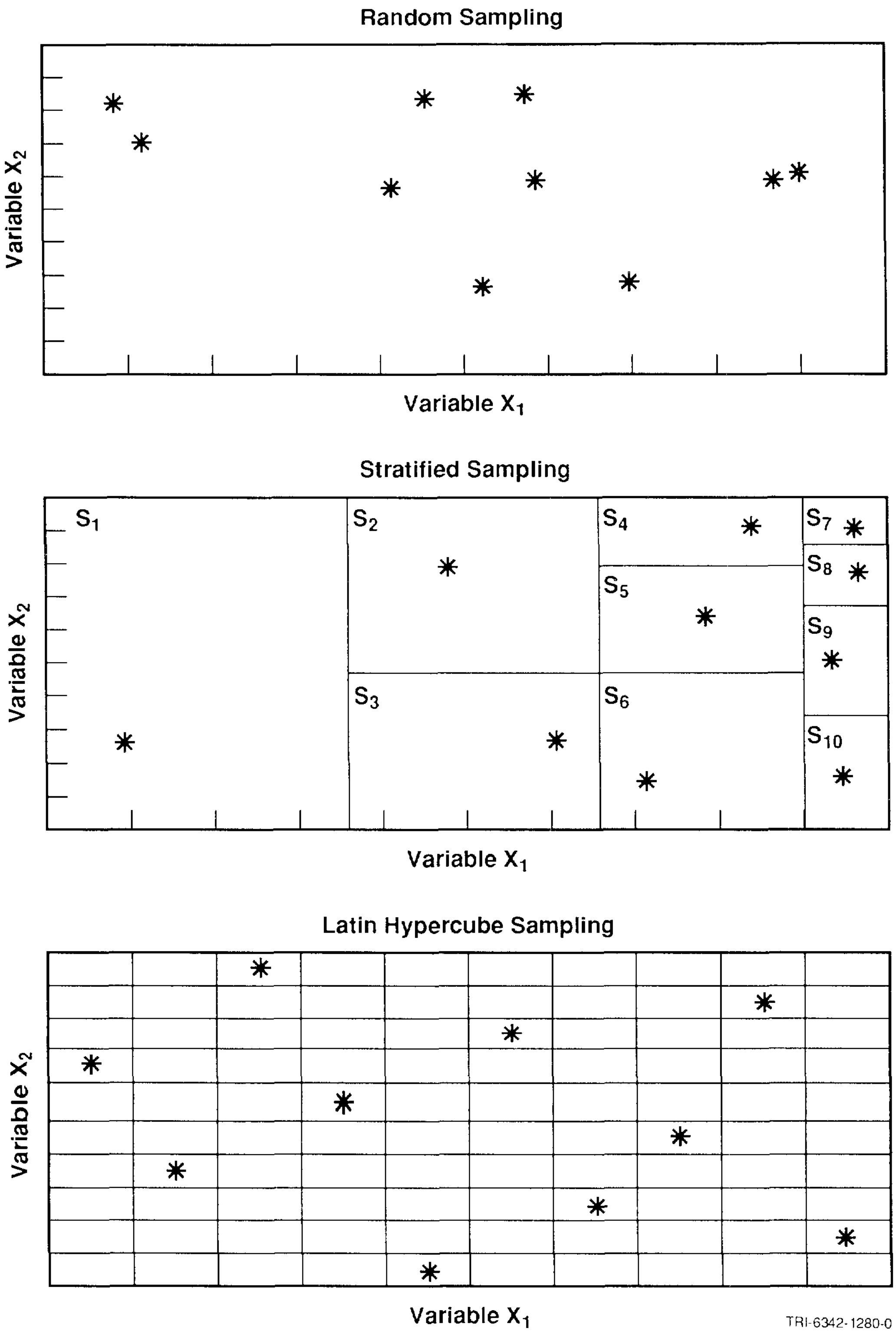

Figure 3-18. Illustration of Random Sampling, Stratified Sampling, and Latin Hypercube Sampling for a Sample of Size 10 from Two Uniformly Distributed Variables.

In response to this situation, Iman and Conover (1982b) have proposed a restricted pairing technique for controlling the correlation structure in random and Latin hypercube samples that is based on rank correlation (i.e., on rank-transformed variables) rather than sample correlation (i.e., on the original raw data). With their technique, it is possible to induce an approximation to any desired rank-correlation structure onto the sample. This technique has a number of desirable properties: (1) It is distribution free. That is, it may be used with equal facility on all types of input distribution functions. (2) It is simple. No unusual mathematical techniques are required to implement the method. (3) It can be applied to any sampling scheme for which correlated input variables can logically be considered, while preserving the intent of the sampling scheme. That is, the same numbers originally selected as input values are retained; only their pairing is affected to achieve the desired rank correlations. This means that in Latin hypercube sampling the integrity of the intervals is maintained. If some other structure is used for selection of values, that same structure is retained. (4) The marginal distributions remain intact.

For many, if not most, uncertainty/sensitivity analysis problems, rank-correlation is probably a more natural measure of congruent variable behavior than is the more traditional sample correlation. What is known in most situations is some idea of the extent to which variables tend to move up or down together; more detailed assessments of variable linkage are usually not available. It is precisely this level of knowledge that rank correlation captures.

The exact mathematical procedure used in the Iman/Conover technique to induce a desired rank-correlation structure is described in the original article (Iman and Conover, 1982b) and also in Doctor (1989). The impact of various rank-correlation assumptions is illustrated in Iman and Davenport (1982).

The WIPP performance assessment uses stratified sampling and Latin hypercube sampling. The decomposition of the sample space S shown in Equation 3-11 into scenarios S_i as indicated in Equation 3-1, and shown in more detail in Equations 3-21 through 3-27, is a form of stratified sampling. The scenario probabilities pS_i in Equation 3-1 are the strata probabilities. Thus, stratified sampling is being used to incorporate stochastic, or Type A, uncertainty into the WIPP performance assessment. Stratified sampling forces the inclusion of low probability, but possibly high consequence, scenarios.

Latin hypercube sampling is being used to incorporate subjective, or Type B uncertainty, into the WIPP performance assessment. Specifically, a Latin hypercube sample of size 60 was generated from the 45 variables in Tables 6.0-1, -2, and -3 in Volume 3 of this report. Further, the restricted pairing technique of Iman and Conover (1982b) was used to prevent spurious correlations within the sample. The resultant sample is listed in Volume 2, Appendix A of this report.

Propagation of Sample Through Analysis

The next step is the propagation of the sample through the analysis. Conceptually, this step is quite simple. Each element of the sample is supplied to the model as input, and the corresponding model predictions are saved for use in later uncertainty and sensitivity studies. This creates a sequence of results of the form

$$y_i = f(x_{i1}, x_{i2}, \ldots, x_{in}) = f(\mathbf{x}_i), \; i = 1, 2, \ldots, m, \qquad (3\text{-}49)$$

where n is the number of input (i.e., sampled) variables and m is the sample size. Typically, there are many model predictions of interest, in which case y_i would be a vector rather than a single number.

In its simplest form, this step involves little more than putting a "DO loop" around the model within which (1) each sample element is read and supplied to the model as input, (2) the model is evaluated, and (3) the results of each model evaluation are written to a file that is saved after all model evaluations have been completed. In practice, this step can be considerably more complicated than this. For example, a sampled variable may not be in exactly the form the model takes as input, or model predictions may not be in the form desired for subsequent uncertainty and sensitivity analysis. In such cases, a preprocessor and a postprocessor can be added to the loop immediately before and immediately after model evaluation to perform the necessary transformations.

A more complex situation sometimes arises when the model under consideration is actually a sequence of individual models, each of which supplies input to the next model in the sequence. When each model produces many distinct cases for analysis by the next model, it is sometimes necessary to use a clustering procedure at the interfaces to control the total number of cases that are propagated through the entire analysis. Otherwise, the number of individual cases can increase until the overall analysis becomes intractable due to computational cost. As an example, the NUREG-1150 analyses (U.S. NRC, 1990) found it necessary to group results at model interfaces to make the Monte Carlo calculations being used to propagate uncertainties practical on a computational basis (Helton et al., 1988; draft of NUREG/CR-4551, U.S. NRC).

The performance of sampling-based uncertainty/sensitivity studies is sometimes facilitated by the use of a special code package to control the overall analysis (Campbell and Longsine, 1990; Holmes, 1987). The Compliance Assessment Methodology Controller (CAMCON) has been developed to facilitate the performance and archival storage of the many complex calculations that are required in the WIPP performance assessment (Rechard, 1989; Rechard et al., 1989). This methodology incorporates data bases, sampling procedures, model evaluations, data storage, uncertainty and sensitivity analysis procedures, and plotting capabilities into a unified structure. The structure and operation of CAMCON is illustrated in Figure 3-19.

Additional information on CAMCON and its use in the 1991 WIPP performance assessment is given in Chapter 5 of this volume.

Uncertainty Analysis

Once a sample has been generated and propagated through a model, uncertainty analysis is straightforward. If random or Latin hypercube sampling is being used, then the expected value and variance for the output variable y can be estimated by

$$E(y) \doteq \sum_{i=1}^{m} y_i/m \tag{3-50}$$

and

$$V(y) \doteq \sum_{i=1}^{m} \left[y_i - E(y)\right]^2/(m - 1), \tag{3-51}$$

respectively. Both estimates are unbiased for random sampling. The estimated expected value is also unbiased for Latin hypercube sampling, but the estimated variance is known to contain a bias. Empirical studies suggest that this bias is small (McKay et al., 1979; Iman and Helton, 1985a). When stratified sampling is used, the factors 1/m and 1/(m-1) in Equations 3-50 and 3-51 must be replaced by weights w_i, i = 1, ..., m, that reflect the probability and number of observations associated with each stratum.

The distributions for the output variables considered in performance assessment are often highly skewed. Due to the disproportionate impact of large but unlikely values, the estimates for the means and variances associated with such distributions tend to be unstable. Here, unstable means that there is a large amount of variation between estimates obtained from independently generated samples. Further, when skewed distributions are under consideration, means and variances give a poor characterization for distribution shape. Basically, means and variances do not contain enough information to characterize highly skewed distributions adequately.

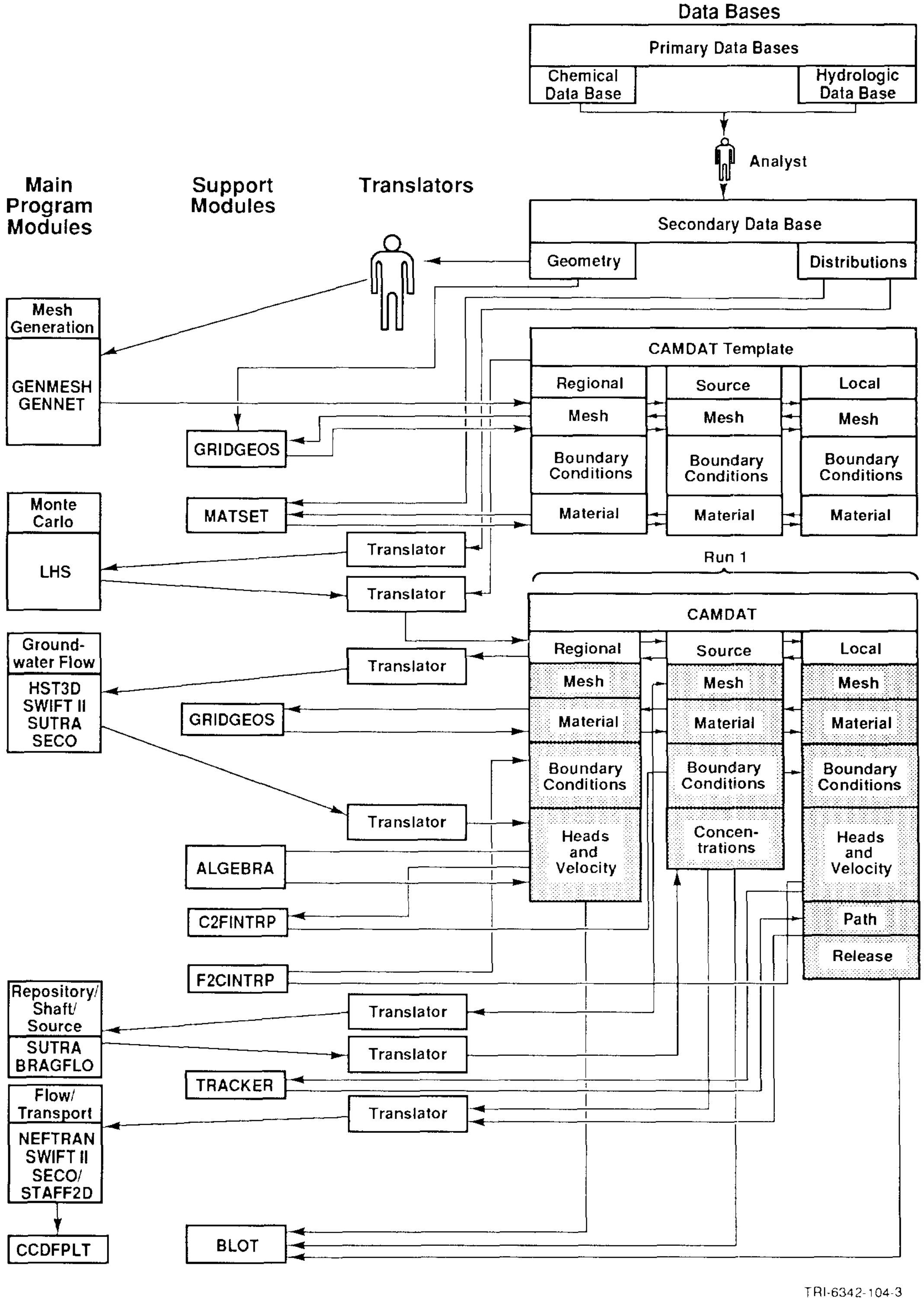

Figure 3-19. Overview of CAMCON.

An estimated distribution function gives a better characterization of the uncertainty in an output variable than a mean and a variance. The distribution function F for the output variable y appearing in Equation 3-49 can be estimated from the relationship

$$F(y) = \begin{cases} 0 & \text{if } y < y_1 \\ i/m & \text{if } y_i \le y < y_{i+1},\ i = 1, 2, \ldots, m-1 \\ 1 & \text{if } y_n \le y, \end{cases} \tag{3-52}$$

where it is assumed that the y_i have been ordered so that $y_i \le y_{i+1}$. This creates a plot that displays all the information contained in Equation 3-49 about the uncertainty in y. An example estimated distribution function is shown in Figure 3-20. The abscissa displays the values for the output variable, and the ordinate displays cumulative probability, which is the probability of obtaining a value equal to or less than a value on the abscissa. The step height is equal to the probability associated with the individual sample elements. If stratified sampling was being used, each observation would be assigned a weight that equalled the probability of the stratum from which it was obtained divided by the number of observations taken from that stratum.

Random sampling, stratified sampling, and Latin hypercube sampling all yield unbiased estimates for distribution functions for predicted variables. When the restricted pairing technique developed by Iman and Conover (1982b) is used to control correlations within the sample, a small bias may be introduced. However, the amount of this bias does not appear to be significant (Iman and Conover, 1982b; Iman and Helton, 1985a).

An alternate, and equivalent, way to display uncertainty is with a complementary cumulative distribution function (CCDF), which is simply 1 minus the cumulative distribution function (cdf). A common practice is to use CCDFs to display stochastic (i.e., Type A) uncertainty and cdf's to display subjective (i.e., Type B) uncertainty. CCDFs are often used to display the results of performance assessments because they answer the question "How likely is it to be this bad or worse?" Also, it is easier to read the probabilities for unlikely but high consequence events from CCDFs than from cdf's. The construction of a CCDF is described in conjunction with Figure 3-1. As discussed in Section 3.1.4-Risk and the EPA Limits, the EPA release limits can be formulated in terms of CCDFs. When both stochastic and subjective uncertainty are present in an analysis, the stochastic uncertainty can be represented with a CCDF, and the subjective uncertainty can be represented with a family or distribution of CCDFs. Examples of representations of this type are given in Figures 3-4 and 3-9.

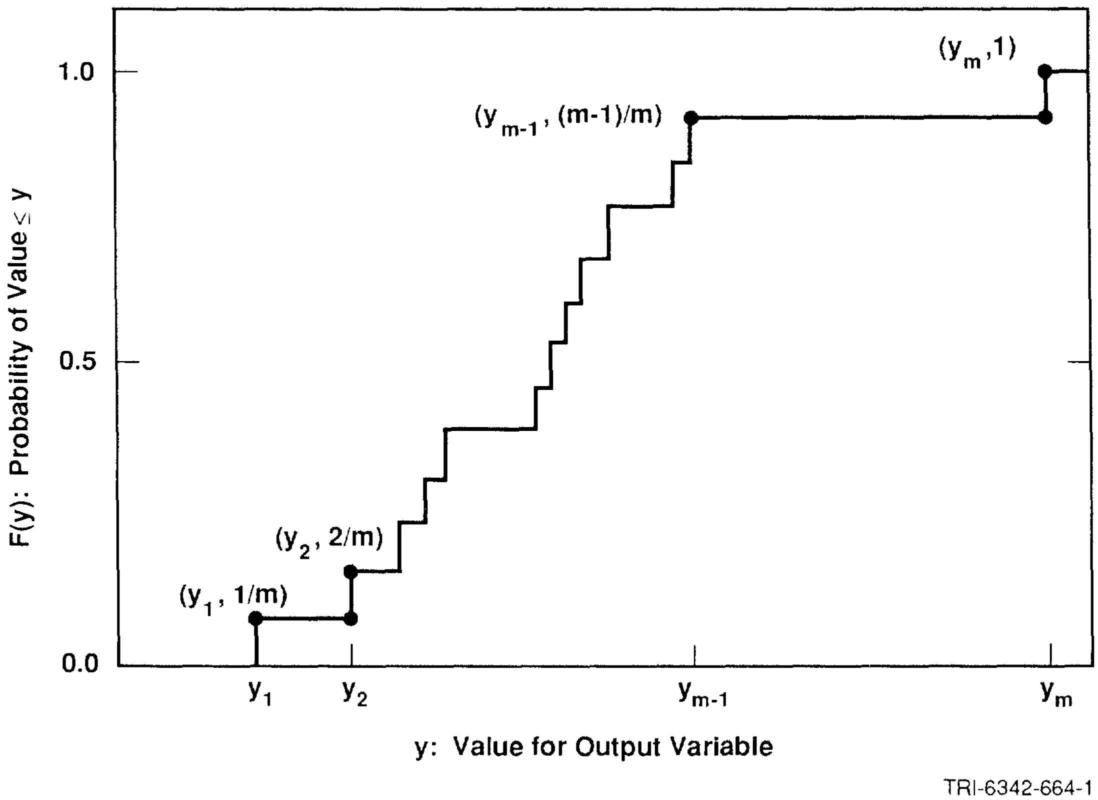

Figure 3-20. Example of an Estimated Distribution Function (Helton et al., 1991).

A cumulative distribution function readily displays the quantiles of a distribution. However, a distribution's mode (i.e., the subrange of a variable in which its probability is most concentrated) is more difficult to identify visually, although it can be done. Further, the mean is not apparent at all. Figure 3-21 shows an alternate uncertainty display that incorporates a distribution function, a density function, and a mean into a single figure (Ibrekk and Morgan, 1987). One advantage of the estimated distribution function is that it displays the results of every observation in an unaltered form. In contrast, the shape of the density function can be sensitive to the gridding selected for use unless a smoothing algorithm is used.

As illustrated in Figure 3-22, box plots (Iman and Conover, 1983) provide an alternate way to display the information in a distribution function. The endpoints of the boxes in Figure 3-22 are formed by the lower and upper quartiles of the data, that is, $x_{.25}$ and $x_{.75}$. The vertical line within the box represents the median, $x_{.50}$. The sample mean is identified by the large dot. The bar on the right of the box extends to the minimum of $x_{.75} + 1.5(x_{.75} - x_{.25})$ and the maximum observation. In a similar manner, the bar on the left of the box extends to the maximum of $x_{.25} - 1.5(x_{.75} - x_{.25})$ and the minimum observation. The observations falling outside of these bars are shown with x's. In symmetric distributions, these values would be considered as outliers. Box plots contain the same information as a distribution function, although in a somewhat reduced form. Further, their flattened shape makes it convenient to present and compare different distributions in a single figure.

Concern is often expressed with respect to the accuracy of the estimates for distribution functions obtained in Monte Carlo analyses. When random sampling is used, Kolmogorov-Smirnov bounds can be used to place confidence intervals about estimated distribution functions (Conover, 1980). Other techniques also exist for use with random sampling (Woo, 1991; Cheng and Iles, 1983). When Latin hypercube sampling is used, replicated sampling can be used to place confidence intervals about estimated distribution functions (Iman, 1982; Iman and Helton, 1991). Use of a technique called fast probability integration provides an alternative to Monte Carlo procedures for the calculation of the tails of distributions (Wu et al., 1990; Wu, 1987; Wu and Wirsching, 1987; Chen and Lind, 1983; Rackwitz and Fiessler, 1978). However, this technique does not appear to have been applied to a problem as complex as estimating the uncertainty in the results of a performance assessment.

The capability to generate means, variances, CCDFs, cdf's, and box plots has been incorporated into the CAMCON structure.

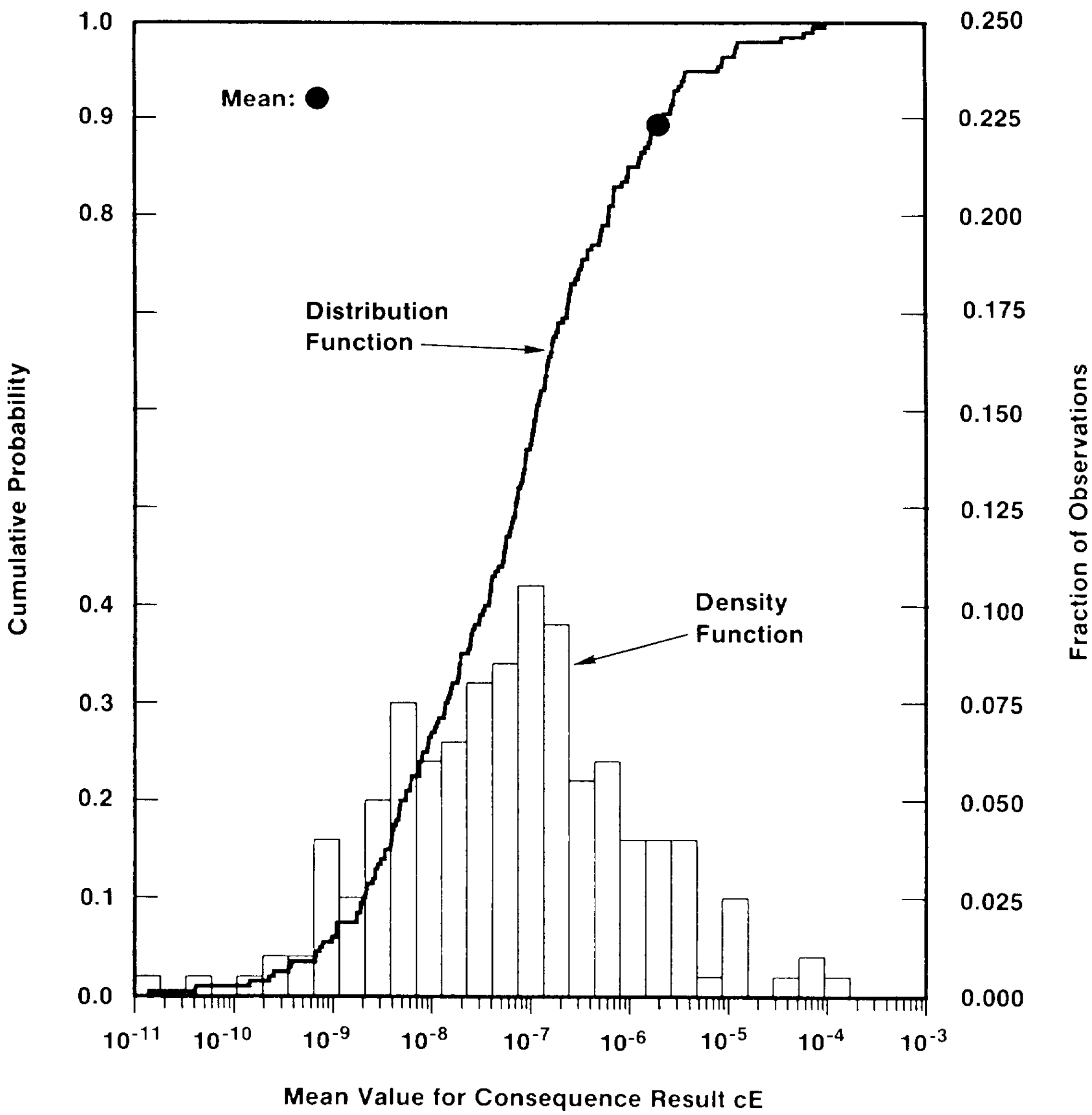

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Figure 3-21. Example Uncertainty Display Including Estimated Distribution Function, Density Function, and Mean (plotted from results contained in Breeding et al., 1990).

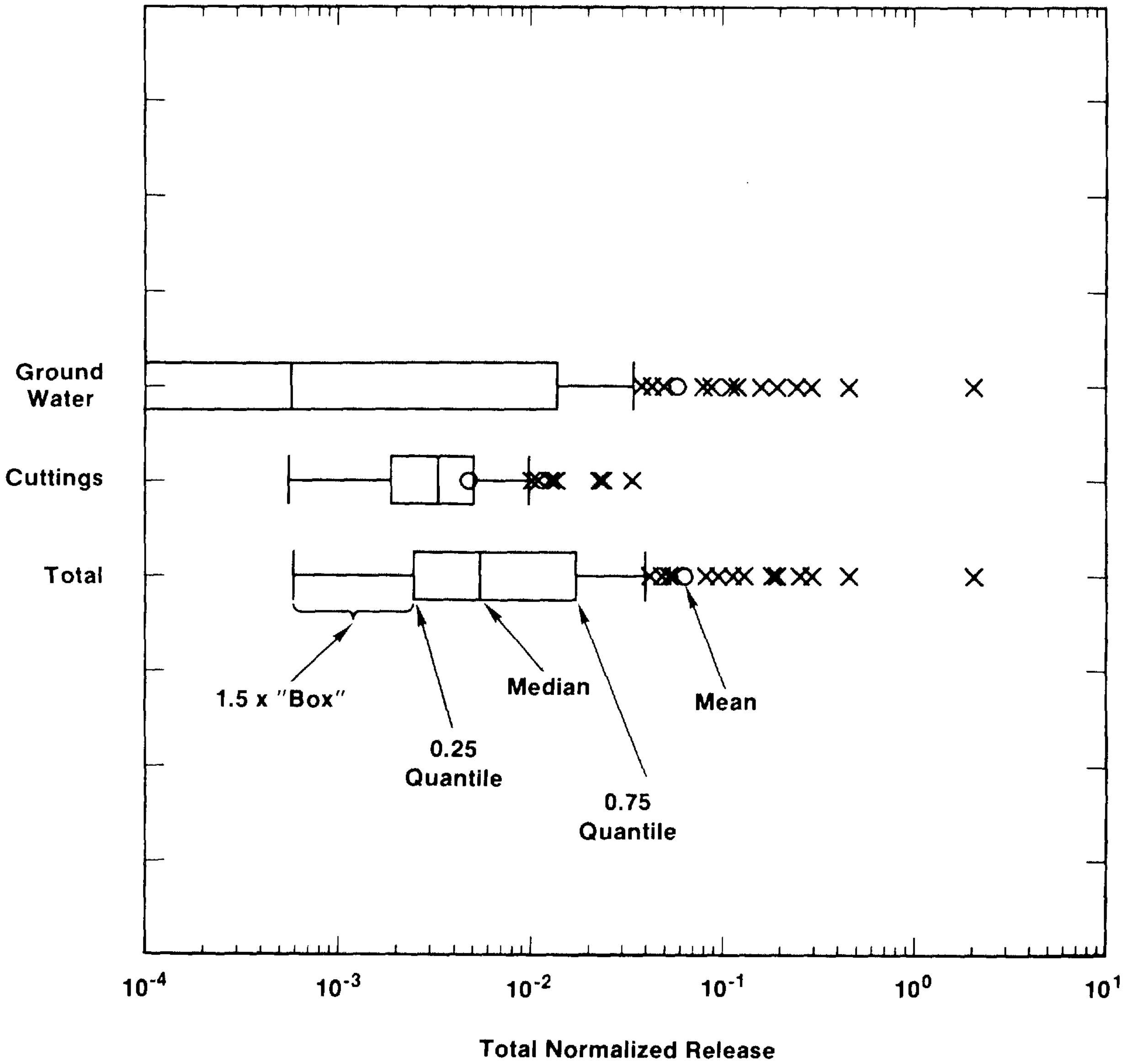

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Figure 3-22. Example of Box Plots (hypothetical results).

Sensitivity Analysis

The final step in a Monte Carlo study is sensitivity analysis. The generation of scatterplots is undoubtedly the simplest sensitivity analysis technique. This approach consists of generating plots of the points (x_{ij}, y_i), $i = 1, \ldots, m$, for each input variable x_j. An example of a scatterplot showing a well-defined relationship between an input and an output variable is shown in Figure 3-23. In contrast, the individual points will be randomly spread over the plot when there is no relationship between the input and the output variable.

Sometimes scatterplots alone will completely reveal the relationships between model input and model output. This is often the case when only one or two inputs completely dominate the outcome of the analysis. Further, scatterplots often reveal nonlinear relationships, thresholds, and variable interactions that facilitate the understanding of model behavior and the planning of more sophisticated sensitivity studies. Iman and Helton (1988) provide an example where the examination of scatterplots revealed a rather complex pattern of variable interactions. The examination of scatterplots is a good starting point in any Monte Carlo sensitivity study. The examination of such plots when Latin hypercube sampling is used can be particularly revealing due to the full stratification over the range of each independent variable.

Sensitivity analyses performed as part of Monte Carlo studies are often based on regression analysis. In this approach, least squares procedures are used to construct a model of the form

$$y = b_0 + \sum_j b_j x_j \tag{3-53}$$

from the mapping between analysis inputs and analysis results shown in Equation 3-49, where the x_j are the input variables under consideration and the b_j are coefficients that must be determined. The coefficients b_j and other aspects of the construction of the regression model shown in Equation 3-53 can be used to indicate the importance of the individual variables x_j with respect to the uncertainty in y.

The preceding regression model can be algebraically reformulated as

$$(y - \bar{y})/\hat{s} = \sum_j (b_j \hat{s}_j/\hat{s})(x_j - \bar{x}_j)/\hat{s}_j, \tag{3-54}$$

where

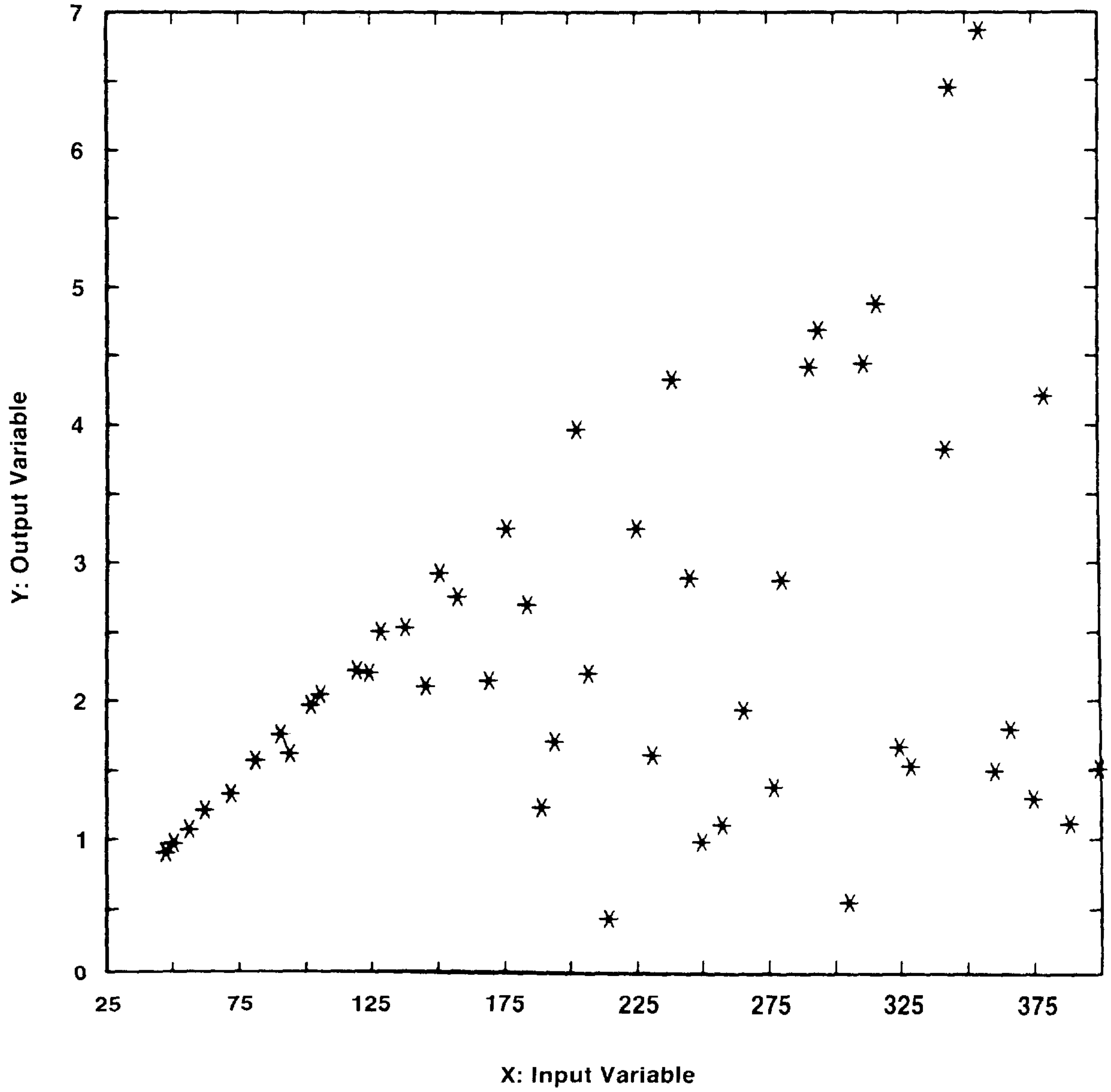

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Figure 3-23. Example Scatterplot (adapted from Helton et al., 1989).

$$\bar{y} = \sum_i y_i/m, \qquad \hat{s} = \left[\sum_i (y_i - \bar{y})^2/(m-1)\right]^{1/2},$$

$$\bar{x}_j = \sum_i x_{ij}/m, \qquad \hat{s}_j = \left[\sum_i (x_{ij} - \bar{x}_j)^2/(m-1)\right]^{1/2}.$$

The coefficients $\hat{b}_j\hat{s}_j/s$ appearing in Equation 3-54 are called standardized regression coefficients. When the x_j are independent, the absolute value of the standardized regression coefficients can be used to provide a measure of variable importance. Specifically, the coefficients provide a measure of importance based on the effect of moving each variable away from its expected value by a fixed fraction of its standard deviation while retaining all other variables at their expected values. Calculating standardized regression coefficients is equivalent to performing the regression analysis with the input and output variables normalized to mean zero and standard deviation one.

The following identity holds for the least square regression model shown in Equation 3-53 and plays an important role is assessing the adequacy of such models:

$$\sum_i (y_i - \bar{y})^2 = \sum_i (\hat{y}_i - \bar{y})^2 + \sum_i (y_i - \hat{y}_i)^2, \tag{3-55}$$

where $\hat{y}_i$ denotes the estimate of y_i obtained from the regression model and $\bar{y}$ is the mean of the y_i. Since the summation $\Sigma_i (y_i - \hat{y}_i)^2$ provides a measure of variability about the regression line, the ratio

$$R^2 = \sum_i (\hat{y}_i - \bar{y}_i)^2/\sum_i (y_i - \bar{y})^2 \tag{3-56}$$

provides a measure of the extent to which the regression model can match the observed data. Specifically, when the variation about the regression line is small (i.e., when $\Sigma_i(y_i - \hat{y}_i)^2$ is small relative to $\Sigma_i(\hat{y}_i - \bar{y}_i)^2$), then the corresponding R^2 value is close to 1, which indicates that the regression model is accounting for most of the variability in the y_i. Conversely, an R^2 value close to zero indicates that the regression model is not very successful in accounting for the variability in the y_i. The designation coefficient of multiple determination is sometimes used for R^2 values.

Regression analyses often perform poorly when the relationships between the input and output variables are nonlinear. This is not surprising since regression analysis is based on developing linear relationships between variables. The problems associated with poor linear fits to nonlinear data can often be avoided with the technique of rank regression (Iman and Conover, 1979). Rank regression is a simple concept: data are replaced with their corresponding ranks and then the usual regression procedures are performed on these ranks. Specifically, the smallest value of each variable is assigned the rank 1, the next largest value is assigned the rank 2, and so on up to the largest value, which is assigned the rank m, where m denotes the number of observations. The analysis is then performed with these ranks being used as the values for the variables in the regression model. The logarithmic and other transformations can also be used to linearize the relationships betweeen the variables in a regression analysis.

The ideas of correlation and partial correlation are useful concepts that often appear in sampling-based sensitivity studies. For a sequence of observations (x_i, y_i), $i = 1, \ldots, m$, the (sample) correlation r_{xy} between x and y is defined by

$$r_{xy} = \frac{\sum_{i=1}^{m} (x_i - \bar{x})(y_i - \bar{y})}{\left[\sum_{i=1}^{m} (x_i - \bar{x})^2\right]^{1/2} \left[\sum_{i=1}^{m} (y_i - \bar{y})^2\right]^{1/2}}, \quad (3\text{-}57)$$

where $\bar{x}$ and $\bar{y}$ are defined in conjunction with Equation 3-54. The correlation coefficient r_{xy} provides a measure of the linear relationship between x and y.

The nature of the correlation coefficient r_{xy} is most readily understood by considering the regression

$$y = b_0 + b_1 x. \quad (3\text{-}58)$$

The definition of r_{xy} in Equation 3-57 is equivalent to the definition

$$r_{xy} = \mathrm{sign}(b_1)(R^2)^{1/2}, \quad (3\text{-}59)$$

where $\mathrm{sign}(b_1) = 1$ if $b_1 \geq 0$, $\mathrm{sign}(b_1) = -1$ if $b_1 < 0$, and R^2 is the coefficient of determination that results from regressing y on x (Helton et al., 1991). With respect to interpretation, the correlation coefficient r_{xy} provides a measure of the linear relationship between x and y, and the regression coefficient b_1 characterizes the effect that a unit change in x will have on y.

When more than one input variable is under consideration, partial correlation coefficients can be used to provide a measure of the linear relationships between the output variable y and the individual input variables. The partial correlation coefficient between y and an individual variable x_p is obtained from the use of a sequence of regression models. First, the following two regression models are constructed:

$$\hat{y} = b_0 + \sum_{j \neq p} b_j x_j \quad \text{and} \quad \hat{x}_p = c_0 + \sum_{j \neq p} c_j x_j . \qquad (3\text{-}60)$$

Then, the results of the two preceding regressions are used to define the new variables $y - \hat{y}$ and $x_p - \hat{x}_p$. By definition, the partial correlation coefficient between y and x_p is the correlation coefficient between $y - \hat{y}$ and $x_p - \hat{x}_p$. Thus, the partial correlation coefficient provides a measure of the linear relationship between y and x_p with the linear effects of the other variables removed. The preceding provides a rather intuitive development of what a partial correlation coefficient is. A formal development of partial correlation coefficients and the relationships between partial correlation coefficients and standardized regression coefficients is provided by Iman et al. (1985).

The partial correlation coefficient provides a measure of the strength of the linear relationship between two variables after a correction has been made for the linear effects of the other variables in the analysis, and the standardized regression coefficient measures the effect on the dependent variable that results from perturbing an independent variable by a fixed fraction of its standard deviation. Thus, partial correlation coefficients and standardized regression coefficients provide related, but not identical, measures of variable importance. In particular, the partial correlation coefficient provides a measure of variable importance that tends to exclude the effects of other variables, the assumed distribution for the particular input variable under consideration, and the magnitude of the impact of an input variable on an output variable. In contrast, the value for a standardized regression coefficient is significantly influenced by both the distribution assigned to an input variable and the impact that this variable has on an output variable. However, when the input variables in an analysis are uncorrelated, an ordering of variable importance based on either the absolute value of standardized regression coefficients or the absolute value of partial correlation coefficients will yield the same ranking of variable importance, even though the standardized regression coefficients and partial correlation coefficients for individual variables may be quite different (Iman et al., 1985).

Many output variables are functions of time or location. A useful way to present sensitivity results for such variables is with plots of partial correlation coefficients or standardized regression coefficients as functions of time or location. An example of such a presentation is given in Figure 3-24. The upper set of curves in Figure 3-24 contains standardized regression coefficients (SRCs) and partial correlation coefficients (PCCs) plotted as a function of time for raw (i.e., untransformed) data. The lower set contains similar results but for analyses performed with rank-transformed data. As can be seen from the curves in Figure 3-24, the standardized regression coefficients and partial correlation coefficients display similar patterns of behavior. Further, the analysis with rank-transformed data reveals a much stronger relationship between the two variables than does the analysis with raw data.

Plots of the form shown in Figure 3-24 can be very useful in displaying the results of sensitivity studies for families of CCDFs that are used to display the uncertainty in the outcome of a performance assessment. For example, standardized regression coefficients or partial correlation coefficients can be used to determine the importance of individual input variables with respect to the exceedance probabilities for individual consequence values appearing on the abscissa in Figure 3-4. The values of these coefficients can then be plotted above the corresponding consequence values. Figure 3-25 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.

When many input variables are involved, the direct construction of a regression model as shown in Equation 3-53 containing all input variables may not be the best approach for several reasons. First, the large number of variables makes the regression model tedious to examine and unwieldy to display. Second, it is often the case that only a relatively small number of input variables have an impact on the output variable. As a result, there is no reason to include the remaining variables in the regression model. Third, correlated variables result in unstable regression coefficients (i.e., coefficients whose values are sensitive to the specific variables included in the regression model). When this occurs, the regression coefficients in a model containing all the input variables can give a misleading representation of variable importance. Fourth, an overfitting of the data can result when variables are arbitrarily forced into the regression model. This phenomenon occurs when the regression model attempts to match the predictions associated with individual sample elements rather than match the trends shown by the sample elements collectively.

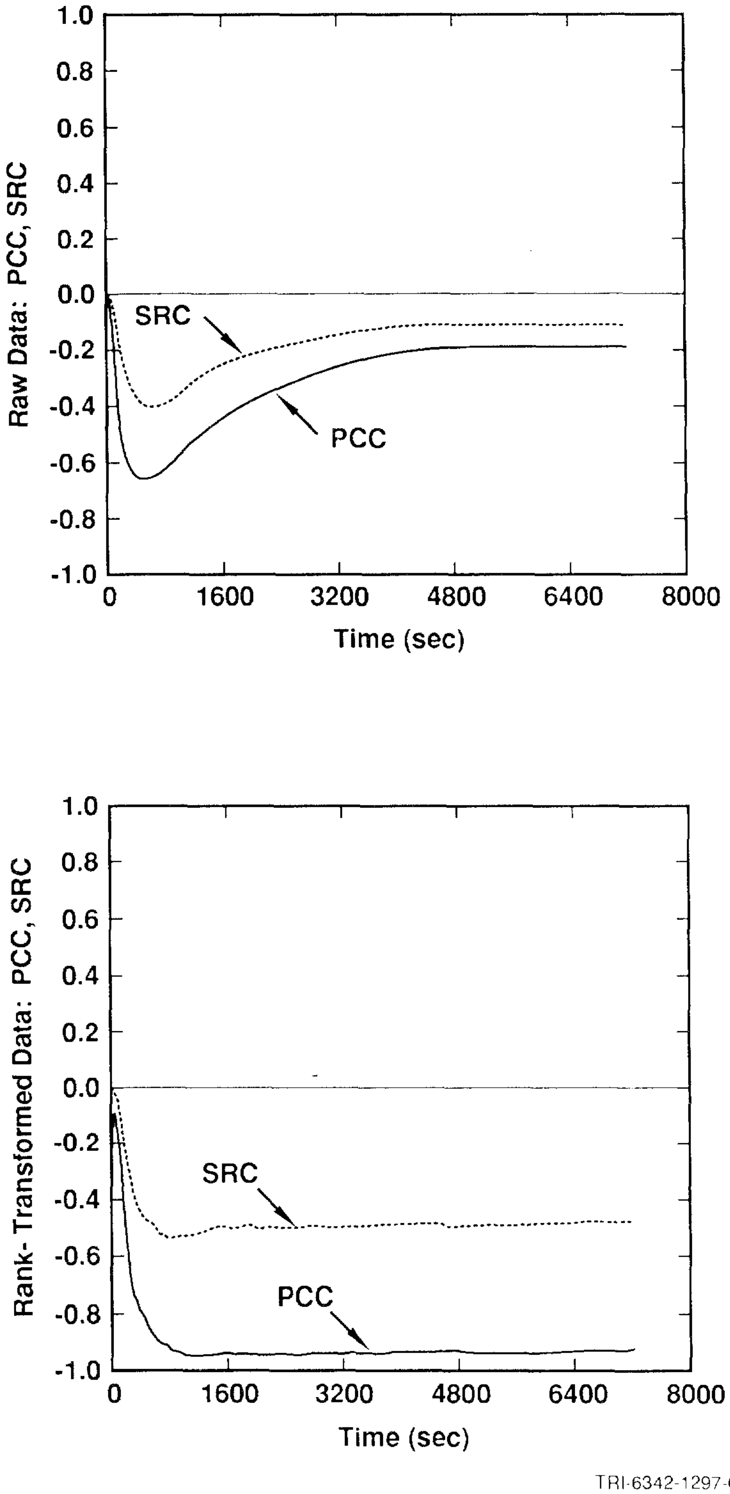

Figure 3-24. Example of Partial Correlation Coefficients (PCCs) and Standardized Regression Coefficients (SRCs) Plotted as a Function of Time for Raw and Rank-Transformed Data (adapted from Helton et al., 1989).

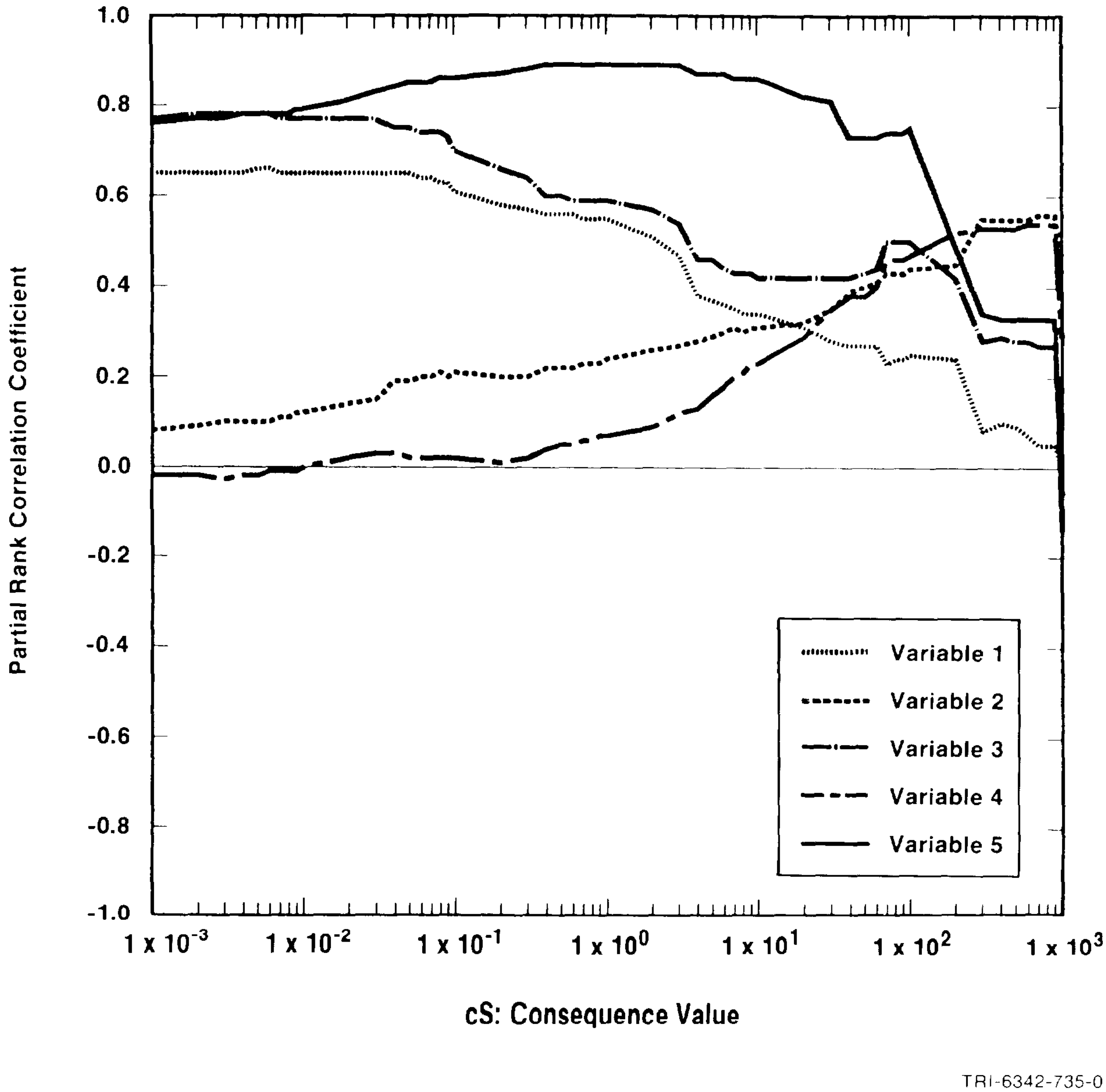

Figure 3-25. Example Sensitivity Analysis for the CCDFs in Figure 3-4 (after Breeding et al., 1990).

Stepwise regression analysis (Draper and Smith, 1981; Neter and Wasserman, 1974) provides an alternative to constructing a regression model containing all the input variables. With this approach, a sequence of regression models is constructed. The first regression model contains the single input variable that has the largest impact on the output variable. The second regression model contains the two input variables that have the largest impact on the output variable: the input variable from the first step plus whichever of the remaining variables has the largest impact on the variation not accounted for by the first variable. The third regression model contains the three input variables that have the largest impact on the output variable: the two input variables from the second step plus whichever of the remaining variables has the largest impact on the variation not accounted for by the first two variables. Additional models in the sequence are defined in the same manner until the point is reached at which further models are unable to meaningfully increase the amount of the variation in the output variable that can be accounted for. Further, at each step of the process, the possibility exists for an already selected variable to be dropped out if it no longer has a significant impact on the uncertainty in the output variable; this only occurs when correlations exist between the output variables.

Several aspects of stepwise regression analysis provide insights on the importance of the individual variables. First, the order in which the variables are selected in the stepwise procedure provides an indication of their importance, with the most important variable being selected first, the next most important variable being selected second, and so on. Second, the R^2 values (see Equation 3-69 in Helton et al., 1991) at successive steps of the analysis also provide a measure of variable importance by indicating how much of the variation in the dependent variable can be accounted for by all variables selected through each step. When the input variables are uncorrelated, the differences in the R^2 values for the regression models constructed at successive steps equal the fraction of the total variability in the output variable that can be accounted for by the individual input variables being added at each step (see Equation 3-75 in Helton et al., 1991). Third, the absolute values of the standardized regression coefficients in the individual regression models provide an indication of variable importance. Further, the sign of a standardized regression coefficient indicates whether the input and output variables tend to increase and decrease together (a positive coefficient) or tend to move in opposite directions (a negative coefficient).

A common but important situation occurs when input variables are uncorrelated. In this case, the orderings of variable importance based on order of entry into the regression model, size of the R^2 values attributable to the individual variables, the absolute values of the standardized regression coefficients, and the absolute values of the partial correlation coefficients are the same. In situations where the input variables are believed to be uncorrelated, one of the important applications of the previously discussed restricted pairing technique of Iman and Conover (1982b) is to assure that the correlations between variables within a Latin hypercube or random sample are indeed close to zero. When variables are correlated, care must be used in the interpretation of the results of a regression analysis since the regression coefficients can change in ways that are basically unrelated to the importance of the individual variables as correlated variables are added to and deleted from the regression model.

As models involving more variables are developed in a stepwise regression analysis, the possibility exists of overfitting the data. Overfitting occurs when the regression model in essence "chases" the individual observations rather than following an overall pattern in the data. For example, it is possible to obtain a good fit on a set of points by using a polynomial of high degree. However, in doing so, it is possible to overfit the data and produce a spurious model that makes poor predictions.

To protect against overfit, the Predicted Error Sum of Squares (PRESS) criterion can be used to determine the adequacy of a regression model (Allen, 1971). For a regression model containing k variables and constructed from m observations, PRESS is computed in the following manner. For $i = 1,2,\ldots,m$, the ith observation is deleted from the original set of m observations and then a regression model containing the original k variables is constructed from the remaining m - 1 observations. With this new regression model, the value $\hat{y}_k(i)$ is estimated for the deleted observation y_i. Then, PRESS is defined from the preceding predictions and the m original observations by

$$\mathrm{PRESS}_k = \sum_{i=1}^{m} \left[y_i - \hat{y}_k(i) \right]^2 . \tag{3-61}$$

The regression model having the smallest PRESS value is preferred when choosing between two competing models, as this is an indication of how well the basic pattern of the data has been fit versus an overfit or an underfit.

Monte Carlo analyses generate a mapping from analysis inputs to analysis results. Once this mapping is generated and saved, it can be explored with a wide variety of techniques. This section has discussed techniques based on scatterplots, regression, correlation, partial correlation, and stepwise regression. The capability to generate sensitivity analysis results with these techniques has been incorporated into the CAMCON structure.

Acknowledgment: Substantial portions of Chapter 3 are taken from Chapters 1, 2 and 6 of the report *Sensitivity Analysis Techniques and Results for*

Performance Assessment at the Waste Isolation Pilot Plant, SAND90-7103, by J. C. Helton, J. W. Garner, R. D. McCurley, and D. K. Rudeen.

Chapter 3–Synopsis

Conceptual Model for WIPP Performance Assessment

Risk

Risk is represented by a set of ordered triples.

The first element in each triple describes things that may happen to the disposal system in the future (i.e., the scenarios).

The second element in each triple describes how likely these things are to happen (i.e., scenario probability).

The third element in each triple describes the consequences of the occurrences associated with the first element (i.e., EPA normalized releases of radionuclides to the accessible environment).

Complementary cumulative distribution functions (CCDFs) are used to display the information contained in the second and third elements of the ordered triple (scenario probability and consequence).

Uncertainty in Risk

Uncertainty in the results of the risk analysis may result from

the completeness of the occurrences considered,

the aggregation of the occurrences into scenarios for analysis,

the selection of models and imprecisely known parameters for use in the models,

stochastic variation in future occurrences.

Characterization of Uncertainty in Risk

Uncertainty resulting from imprecisely known parameter values results in a family of CCDFs. Variability in this family of CCDFs can be displayed by showing the entire family or by showing the mean and selected quantile curves.

Risk and the EPA Limits

CCDFs will be compared to the limits placed on cumulative normalized releases of radionuclides to the accessible environment by the Containment Requirements of the Standard.

Probability and Risk

The sample space for the WIPP performance assessment consists of all possible 10,000-yr histories of the WIPP following decommissioning.

The infinite number of possible 10,000-yr histories are grouped into subsets of the sample space (scenarios) for probability assignment and consequence analysis.

There is no inherently "correct" grouping of the time histories into subsets. The use of more scenarios results in finer resolution in the CCDF (more steps in a single curve) but may also result in a larger computational burden.

Definition of Scenarios

Summary Scenarios

The first stage in scenario definition for the WIPP has five steps:

compiling or adopting a comprehensive list of events and processes that could potentially affect the disposal system during the next 10,000 years,

classifying the events and processes,

screening the events and processes to identify those that can be eliminated from consideration, developing scenarios by combining the events and processes that remain after screening,

screening the scenarios to identify those that can be eliminated from consideration.

The first step corresponds to defining the sample space for the analysis. The remaining steps define the summary scenarios.

Computational Scenarios

To increase resolution in the CCDF, the summary scenarios are further decomposed into computational scenarios.

For 1991, computational scenarios are distinguished by the time and number of intrusions, whether or not a brine reservoir is encountered below the waste, and the activity level of waste intersected.

Determination of Scenario Probabilities

Probabilities for Summary Scenarios

Probabilities for summary scenarios were reported in the *1990 Preliminary Comparison*.

Probabilities for Computational Scenarios

Probabilities for the 1991 computational scenarios are based on the assumption that intrusion follows a Poisson process (i.e., boreholes are random in time and space) with a rate constant, λ, that is sampled as an uncertain parameter in the 1991 calculations.

Calculation of Scenario Consequences

Overview of Models

The models used in the WIPP performance assessment exist at four levels:

conceptual models that characterize our understanding of the system,

mathematical models that represent the processes of the conceptual model,

numerical models that provide approximations to the solutions of the selected mathematical models, computer models that implement the numerical models.

Organization of Calculations for Performance Assessment

Calculations are organized so that results for computational scenarios can be constructed from a minimum number of calculations for each time interval.

Uncertainty and Sensitivity Analyses

Available Techniques

Available techniques for uncertainty and sensitivity analysis include differential analysis, Monte Carlo analysis, response surface methodology, and Fourier amplitude sensitivity tests.

The WIPP performance assessment uses Monte Carlo analysis techniques because

they are appropriate for analysis problems in which large uncertainties are associated with the independent variables,

they provide direct estimates for distribution functions,

they do not require sophisticated techniques beyond those required for the analysis of the problem of interest,

they can be used to propagate uncertainties through a sequence of separate models.

Monte Carlo Analysis

A Monte Carlo analysis involves five steps:

the selection of variable ranges and distributions,

the generation of a sample from the parameter value distributions,

the propagation of the sample through the analysis,

analysis of the uncertainty in results caused by variability in the sampled parameters, sensitivity analyses to identify those parameters for which variability in the sampled value had the greatest effect on the results.

4. SCENARIOS FOR COMPLIANCE ASSESSMENT

Robert V. Guzowski[1] and Jon C. Helton[2]

[NOTE: The text of Chapter 4 is followed by a synopsis that summarizes essential information, beginning on page 4-85.]

4.1 Definition of Scenarios

4.1.1 CONCEPTUAL BASIS FOR SCENARIO DEVELOPMENT

As shown in Equation 3-1 and discussed in Chapter 3 of this volume, the results of the WIPP performance assessment can be represented by a set of ordered triples, where the first element in each triple is a set S_i of similar occurrences (i.e., a scenario), the second element is the probability pS_i for S_i, and the third element is a vector $\mathbf{cS}_i$ of consequences associated with S_i. The S_i are obtained by subdividing a set S that contains all possible occurrences during the period of regulatory concern at the WIPP. As discussed in conjunction with Equation 3-11, the set S (i.e., the sample space) consists of all possible 10,000-year time histories at the WIPP beginning at the decommissioning of the facility.

The first stage in scenario development is construction of the set S. Once S is constructed, the scenarios S_i can be obtained by subdividing S. The set S is very large; indeed, S has infinitely many elements. Thus, scenario development must proceed carefully so that excessive resources are not expended on the development and subsequent analysis of scenarios whose impact on the CCDF used for comparison with the EPA release limits can be reasonably anticipated due to low probability, low consequences, or regulatory exclusion.

The following four subsets of S (i.e., scenarios) provide a natural starting point for scenario development: S_B, called the base-case subset, which consists of all elements in S that fall within the bounds of what can be reasonably anticipated to occur at the WIPP over 10,000 years; S_M, called a minimal disruption subset, which consists of all elements in S that involve disruptions that result in no significant perturbation to the consequences associated with the corresponding element in the base-case subset S_B; S_E, a regulatory exclusion subset consisting of all elements in S that are excluded from consideration by regulatory directive (e.g., human intrusions more

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severe than the drilling of exploratory boreholes); and S_L, called a high consequence, low probability subset, which consists of elements of S not contained in S_B, S_M, or S_E that have the potential to result in large consequences (e.g., normalized releases to the accessible environment greater than 10) but whose collective probability is small (e.g., the probability of S_L is less than 0.0001). Everything that remains in S after the identification of S_B, S_M, S_E, and S_L now becomes a subset that can be designated S_O, where the subscript 0 was selected to represent the word "Other". In set notation,

$$S_O = (S_B \cup S_M \cup S_E \cup S_L)^c, \qquad (4\text{-}1)$$

where the superscript c is used to designate the complement of a set. This produces a decomposition of S into five subsets.

A conceptual representation for this decomposition is shown in Figure 4-1. Due to regulatory guidance, S_E can be excluded from consideration in compliance assessment, which is equivalent to assuming that its probability pS_E is equal to zero. The actual size of S_L relative to that of S_B and S_M may be large. However, the probability of S_L is small. Thus, the possible consequences associated with S_L will not result in violation of the EPA release limits. Releases associated with S_B, and hence with S_M, are anticipated to be nonexistent or very small for the WIPP. As a result, determination of whether or not the WIPP meets the EPA release limits will depend on additional scenarios S_i, i=1, ..., nS, obtained by further refining (i.e., subdividing) the subset S_O and possibly the subset $S_B \cup S_M$. This further refinement is necessary since it is unlikely that S_O will be so homogeneous that a single normalized release will provide a suitable representation for the consequences associated with each element (i.e., time history) in S_O.

A representation of the CCDF for comparison with the EPA release limits that results from the subsets S_B, S_M, S_1, ..., S_{nS}, S_L is given in Figure 4-2. The subset S_E is not included due to its exclusion by regulatory directive. As shown in Figure 4-2, the probabilities for S_B and S_M determine the vertical drop in the CCDF above zero (with the assumption that the base-case leads to no release, which is apparently true for the WIPP (Bertram-Howery et al., 1990) but may not be true for other sites), and the right most extent of the CCDF is determined by S_L. As long as pS_L is small (e.g., less than 10^{-4}) and the releases associated with the S_i are not close to violating the EPA release limits, the actual value assigned to cS_L has no impact on whether or not the CCDF for all scenarios crosses the EPA release limits. The representation in Figure 4-2 is rather stylized. In practice, both S_B and S_L may be subdivided into additional subsets that give rise to

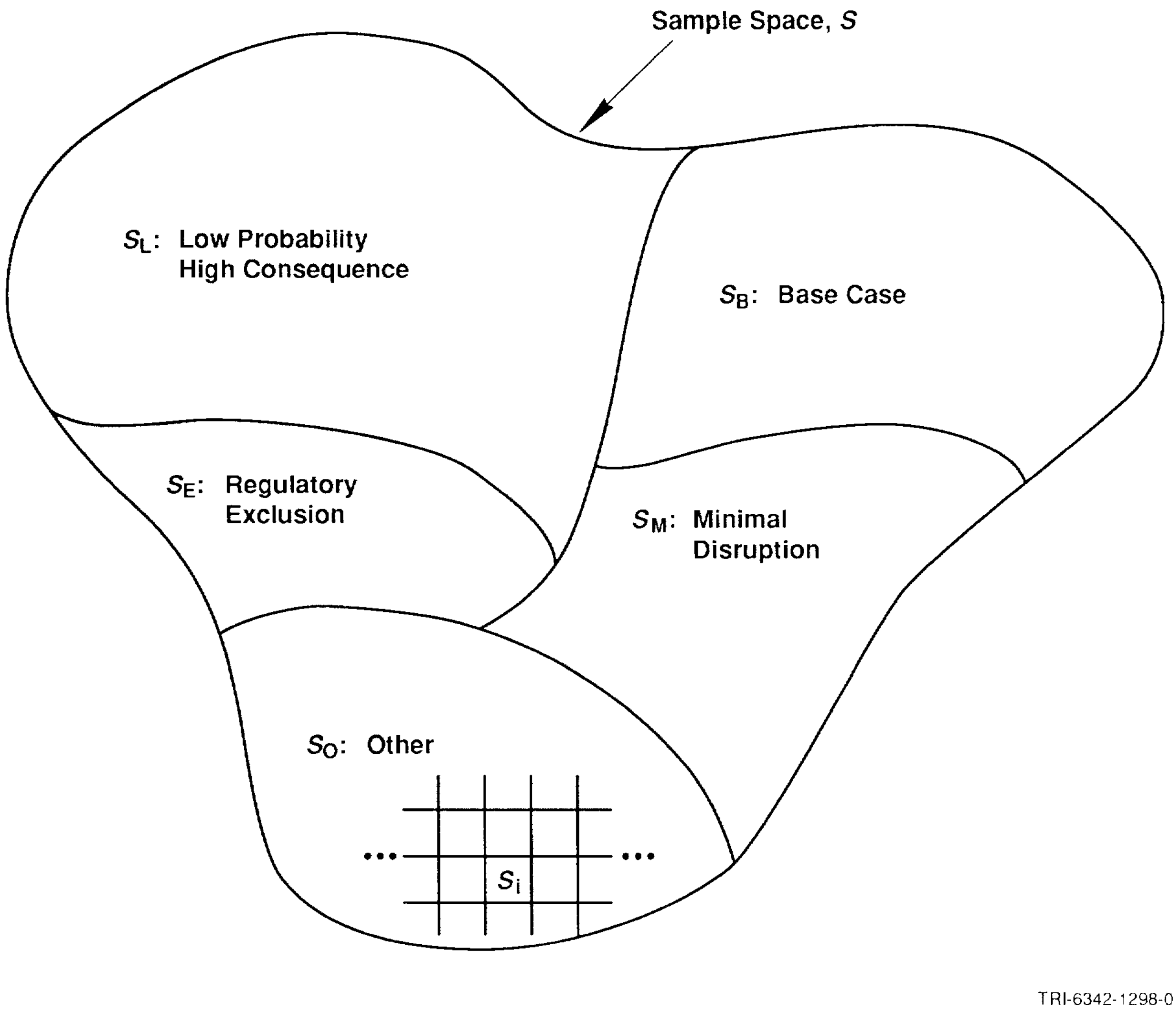

Figure 4-1. Decomposition of the Sample Space S into High-Level Subsets, where S_B Designates the Base-Case Subset, S_M Designates a Minimal Disruption Subset, S_E Designates a Regulatory Exclusion Subset, S_L Designates a Low-Probability, High-Consequence Subset, and S_O designates $(S_B \cup S_M \cup S_E \cup S_L)^c$.

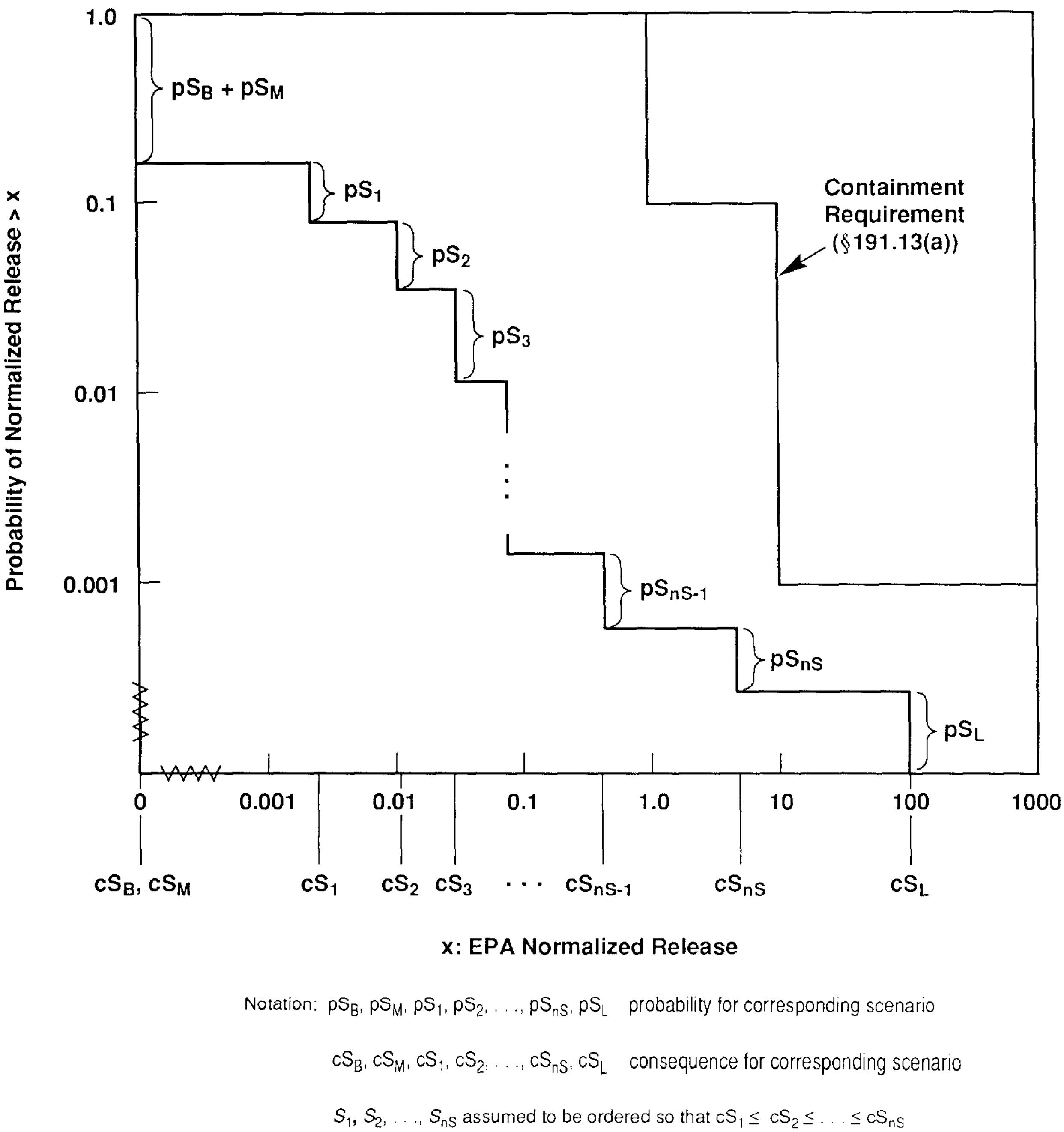

Figure 4-2. Construction of a CCDF for Comparison with the EPA Release Limits.

additional steps. Further, some of the release values for the S_i could overlap those for S_L. However, the overall pattern remains the same, with S_B and S_M determining the upper left of the CCDF, S_L determining the lower right, and the bulk of the CCDF being determined by the S_i.

Sometimes terminology is used that suggests S_M and S_L are excluded from consideration in the construction of a CCDF for comparison with the EPA release limits. Such an exclusion should not take place. The probability for S_M can be incorporated into the probability for S_B; this is usually done by simply not correcting the calculated probability of S_B for the possible occurrence of S_M. The effect of S_L is a small extension on the lower right of the CCDF. Whether or not this effect is shown on the CCDF, it was included in the construction of the CCDF through the determination that its impact was unimportant. In this regard, the EPA provides guidance that would not stand up to careful probabilistic scrutiny. They indicate that 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 included in a performance assessment. By suitably defining the events and processes selected for consideration, all probabilities can be made less than the specified bound. A more reasonable specification would be on the total probability that could be ignored rather than on individual increments of probability. The intent of the WIPP performance assessment is to bound the total probability of all occurrences that are removed from detailed consideration (i.e., the probability pS_L for S_L) rather than the individual probabilities for a number of different scenarios.

Since S_B, S_M, and S_L may account for a large part of the sample space S and also have readily predicted effects on the CCDF used for comparison with the EPA release limits, an efficient strategy is to determine S_B, S_M, and S_L before the subdivision of S_0 into the scenarios S_i shown in Figure 4-2 is considered. This strategy allows resolution to be built into the analysis where it is important, that is, in the construction of the S_i. In recognition of this, the WIPP performance assessment uses a two-stage approach to scenario development.

The first stage of the analysis focuses on the determination of the sample space S and the subsets S_B, S_M, S_L, and S_0. A tentative division of S_0 into additional summary scenarios is also performed. This stage of the analysis uses a scenario-selection procedure suggested by Cranwell et al. (1990) that consists of the following five steps: (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.

The purpose of the first step is to develop the sample space S, which consists of all possible 10,000-year time histories that involve the identified events and process. The set S is infinite and, in practice, its individual elements cannot be listed. Rather, S is subdivided into the subsets S_B, S_M, S_L, and S_O. This subdivision takes place in Steps 2 and 3. The screening associated with Steps 2 and 3 also removes time histories from S that are physically unreasonable. In Step 4, a preliminary subdivision of the subset S_O into additional summary scenarios is performed. This subdivision is accomplished through a two-part process. In the first part, subsets of S_O (i.e., scenarios) are defined that involve specific events or processes. However, these scenarios are not mutually exclusive. In the second part, a subdivision of S_O into mutually exclusive scenarios S_i is accomplished by forming all possible intersections of the single event/process scenarios and their complements. The fifth and final step in the process is a screening of the scenarios S_i on the basis of probability, consequence, and physical reasonableness. The purpose of this screening is to determine if some of the S_i can be removed from the analysis or assigned to S_M or S_L, with a resultant reduction in the size of S_O. Thus, this final step may involve a redefinition of S_B, S_M, S_L, and S_O.

The first stage of scenario development is described in Section 4.1.2-Definition of Summary Scenarios. If the first stage of scenario development has been performed properly, the impact of the subsets S_M and S_L on the CCDF used for comparison with the EPA release limits can be reasonably anticipated or, for S_B, determined with a small number of calculations. Compliance or noncompliance with the release limits will be determined by S_O. The summary scenarios S_i developed from S_O in the first stage of scenario development are unlikely to be defined at a sufficiently fine level of resolution for use in the actual construction of a CCDF. Therefore, the second stage of scenario development is the division of S_O into mutually exclusive scenarios at a sufficiently fine level of resolution for actual use in CCDF construction.

The first stage of scenario development for the 1991 WIPP performance assessment indicated that drilling intrusions are the only credible disruption associated with S_O. Therefore, the subdivision of S_O into mutually exclusive scenarios for CCDF construction is based on drilling intrusions. This subdivision is developed to provide good resolution at the 0.1 and 0.001 probabilities on the CCDF and is based on (1) number of drilling intrusions, (2) time of the drilling intrusions, (3) whether or not a single waste panel is penetrated by two or more boreholes, of which at least one penetrates a brine pocket and at least one does not, and (4) the activity level of the waste penetrated by the boreholes. The development of scenarios for actual use in CCDF construction is described in Section 4.1.8-Definition of Computational Scenarios.

As shown in Equation 3-1, the second element of the conceptual representation being used for the WIPP performance assessment is scenario probability pS_i. Thus, once the scenarios S_i into which S_0 is subdivided are determined, it is necessary to determine their probabilities. In addition, probabilities also must be determined for S_B and S_M. The subset S_L is constructed so that its probability is sufficiently small to have no significant impact on the CCDF used for comparison with the EPA release limits.

As with scenario development, the WIPP performance assessment uses a two-stage procedure to determine scenario probabilities. The first stage operates with the summary scenarios into which S_0 was subdivided in the first stage of scenario development. Here, the purpose is to obtain probabilities that provide guidance on what is important to performance assessment at the WIPP. For example, these probabilities provide guidance at the fifth step of scenario development (i.e., screening scenarios) as to whether or not specific scenarios S_i can be taken from S_0 and moved to S_L. The determination of probabilities in conjunction with the first stage of scenario development for the 1991 WIPP performance assessment is described in Section 4.2.1-Probabilities for Summary Scenarios.

The second stage of probability development is for the scenarios S_i actually used in CCDF construction. Thus, these probabilities are for the scenarios S_i into which S_0 is divided in the second stage of scenario development. As indicated earlier, drilling was the only disruption associated with S_0 for the 1991 WIPP performance assessment. As a result, the probabilities pS_i are derived from assumptions involving rate of drilling, area of pressurized brine under the repository, and distribution of activity levels within the waste. The values used for pS_i are described in Section 4.2.2-Probabilities for Computational Scenarios.

The determination of both scenarios and scenario probabilities is a complex process with significant uncertainties. To help assure that the WIPP performance assessment brings a broad perspective to this task, an expert panel was formed to provide a diversity of views with respect to possible futures at the WIPP. The formation of this panel and the results obtained from its deliberations are summarized in Section 4.3-Expert Judgment on Inadvertent Human Intrusion.

4.1.2 DEFINITION OF SUMMARY SCENARIOS

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[3] 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 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 in Bertram-Howery and Hunter (1989b), Marietta et al. (1989), Cranwell et al. (1990), and Bertram-Howery et al. (1990). In the present document, these combinations are referred to as summary scenarios, including S_B and a coarse resolution of S_O into subsets of outcomes, S_i.

Appendix B of the Standard states that wherever practicable, the results of the performance assessments will be assembled into a complementary cumulative distribution function (CCDF), of which the mean CCDF (see Chapter 3 of this volume) is one possibility, in order to determine compliance. In order to construct a mean CCDF and other summary CCDFs for determining compliance with the Containment Requirements, four criteria must be met by the S_i into which S_O and possibly S_B are subdivided: (1) the set of scenarios analyzed must describe all reasonably possible future states of the disposal system, (2) the scenarios in the analyses should be mutually exclusive so that radionuclide releases and probabilities of occurrence can be conveniently associated with specific scenarios, (3) the cumulative releases of radionuclides (consequences) for each scenario must be estimated, and (4) the probability of occurrence of each scenario must be estimated. Because performance assessments are iterative analyses, the

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[3] Event is used in the regulatory sense throughout this chapter and should not be interpreted as "event" as used in the probabilistic development of risk in Chapter 3.

results of preliminary analyses may suggest areas for additional research, which could in turn suggest new events and processes for inclusion in the performance assessment.

Identifying all possible combinations of events and processes that could affect a disposal system would result in an extremely large number of scenarios S_i, 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 to be excluded from the performance-assessment analyses on the basis of low probability, which corresponds to the subset S_L. In addition, exploratory drilling for natural resources is the most severe type of human intrusion considered, so other human-intrusion modes result in possible outcomes which are contained in S_E. Each criterion is described in Appendix B of the Standard (reproduced in Appendix A of this volume).

Scenarios S_i that are within the scope of Appendix B of the Standard and meet the requirements for constructing a 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. As discussed in Chapter 3, these scenarios are called summary scenarios, and this scenario-selection procedure is the first stage of scenario definition. The second stage is the definition of computational scenarios.

Identifying Events and Processes

Several reports have identified events and processes that could affect the integrity of generic disposal systems (e.g., Burkholder, 1980; IAEA, 1983; Andersson et al., 1989; Cranwell et al., 1990) and disposal systems at specific locations (e.g., Claiborne and Gera, 1974; Bingham and Barr, 1979). In a preliminary effort at identifying the events and processes that need to be considered for the WIPP performance assessment, Hunter (1989) developed a list of 24 events and processes primarily selected from lists published in Claiborne and Gera (1974), Bingham and Barr (1979), Arthur D. Little, Inc. (1980), and Cranwell et al. (1990). This consolidated list was found to be incomplete during preliminary scenario development (Guzowski, 1990) and from external review of the 1990 *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990* (Bertram-Howery et al., 1990). Several events and processes that require evaluation on a site-specific basis were not included in Hunter's (1989) list.

To address the completeness issue, the list of events and processes in Hunter (1989) was replaced, and the events and processes were rescreened. Cranwell et al. (1990) developed a scenario-selection procedure to provide specific components of performance assessments to address the Containment Requirements (§ 191.13) of the EPA Standard. For this reason, the events and processes listed in Cranwell et al. (1990) (Table 4-1) were used as a starting point in the development of disruptive scenarios for the WIPP. This list was developed by a panel of experts that met in 1976 and again in 1977 under the auspices of the U.S. Nuclear Regulatory Commission. The task of this panel was not to identify all possible events and processes that could occur in or near a waste disposal facility but to identify events and processes that could compromise the performance of an engineered disposal facility constructed in deep geologic media for nuclear waste. To address specific concerns about the WIPP, gas generation by the degradation of the waste, waste-related explosions, and nuclear criticality were added to the list produced by the panel.

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 disposal of nuclear waste, this same cycle may be considered as an event. In identifying events and processes for the WIPP performance assessment, 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 of regulatory concern are considered to be processes. The classification of a phenomenon as an event rather than as a process, or vice versa, does not affect scenario development.

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, to assist in completeness arguments, and to provide some insights when developing conceptual models of the disposal system. Categories in the classification schemes for the generic lists mentioned in

TABLE 4-1. POTENTIALLY DISRUPTIVE EVENTS AND PROCESSES

- Natural Events and Processes
  - Celestial Bodies
    - Meteorite Impact
  - Surficial Events and Processes
    - Erosion/Sedimentation
    - Glaciation
    - Pluvial Periods
    - Sea-Level Variations
    - Hurricanes
    - Seiches
    - Tsunamis
    - Regional Subsidence or Uplift
    - Mass Wasting
    - Flooding
  - Subsurface Events and Processes
    - Diapirism
    - Seismic Activity
    - Volcanic Activity
    - Magmatic Activity
    - Formation of Dissolution Cavities
    - Formation of Interconnected Fracture Systems
    - Faulting
- Human-Induced Events and Processes
  - Inadvertent Intrusions
    - Explosions
    - Drilling
    - Mining
    - Injection Wells
    - Withdrawal Wells
  - Hydrologic Stresses
    - Irrigation
    - Damming of Streams and Rivers
  - Repository- and Waste-Induced Events and Processes
    - Caving and Subsidence
    - Shaft and Borehole Seal Degradation
    - Thermally Induced Stress Fracturing in Host Rock
    - Excavation-Induced Stress Fracturing in Host Rock
    - Gas Generation
    - Explosions
    - Nuclear Criticality

Source: Modified from Cranwell et al., 1990.

Step 1 are similar and can be identified as naturally occurring, human induced, and waste and repository induced. Subdivisions of the categories (Table 4-1) also may be useful.

Screening Events and Processes

Events and processes are screened using three criteria based on guidance in the Standard: probability of occurrence, physical reasonableness, and consequence. In addition, EPA's guidance concerning implementation of the Standard does not require consideration of human-intrusion events with consequences more severe than those of exploratory drilling for resources. Low probability events and processes define a set of possible outcomes that is included in S_L. Low consequence events and processes define a set of possible outcomes that is included in S_M. Modes of intrusion other than exploratory drilling define a set of possible outcomes that is included in S_E. Events and processes that are physically unreasonable may be included in S_L or removed entirely from the sample space S depending on the justification for physical unreasonableness. Probability of occurrence of an event or process must be estimated by probabilistic techniques. According to Appendix B of the Standard, events and processes that are estimated to have less than 1 chance in 10,000 of occurring in 10,000 years do not have to be included in the performance assessment. Physical reasonableness as a screening criterion is a qualitative estimate of low probability based on subjective judgment. A logical argument, possibly with supporting calculations, can be used to establish whether the occurrence of a particular event or process at a location within the time period of regulatory concern and with sufficient magnitude to affect the performance of the disposal system is physically reasonable. The third screening criterion is consequence. At this stage of the scenario-development procedure, consequence is based on whether the event or process either alone or in combination with other events or processes may affect the performance of the disposal system; many low consequence events and processes give rise to occurrences in the subset S_M. Simplified conceptual models of the disposal system and simplified mathematical models can be used to determine whether an event or process will affect the groundwater-flow system or alter possible pathways from the panels to the accessible environment.

Although quantitative screening criteria generally are preferable to qualitative criteria, the nature of the individual events and processes being screened and the availability of information and data determine how screening can proceed. On the regional scale of the northern Delaware Basin, the dynamics resulting in the low level and nonregularity of tectonic activity and other physical processes characteristic of this region are poorly understood. Qualitative judgments of screening criteria using interpretations based on geological field relationships, natural analogs, and geographic location are required. The occurrence of human-induced events and processes is dependent on the values, needs, and technological development of future societies. While few if any of this category of events and processes can be screened out on the qualitative grounds of physical unreasonableness, qualitative judgments of the likelihood of conditions for some of these events and processes to occur or the effects of some of these occurrences on the disposal system can be made. In general, screening decisions based on qualitative judgments that are supported by strong logical arguments are as justifiable as screening decisions for certain events and processes that are based on quantitative values derived from sufficiently detailed data bases.

4.1.3 EVALUATION OF NATURAL EVENTS AND PROCESSES

This section evaluates each of the events and processes listed in Table 4-1 with regard to the screening criteria described above. Events and processes with probabilities of occurrence of 1 are part of the base-case scenario. Physically reasonable events and processes with probabilities of occurrence less than 1 and above the cutoff specified in the Standard (less than 1 chance in 10,000 of occurring in 10,000 years) are retained for scenario development. The estimation of numerical values for low-probability events and processes is difficult and often controversial, so caution should be used when screening high-consequence events and processes whose probability of occurrence is estimated to be only slightly below the regulatory cutoff. No consequence modeling was performed specifically as part of screening the events and processes. The following evaluations only consider the disposal system after it has been decommissioned.

Meteorite Impact

Meteorite impacts are a concern to nuclear-waste disposal because of the possibility that such an impact could exhume buried waste or fracture the rock overlying the waste to create pathways for groundwater to reach the waste. Several estimates have been made of the probability of an impact at a disposal site by a meteorite large enough to either exhume the waste or substantially disrupt the disposal system. Hartmann (1979) estimated the probability of a meteorite exhuming part of the waste in a repository of 10 km^2 area and a depth of 600 meters to be 6 x 10^{-13}/year. A Swedish study (Karnbranslesakerhet, 1978) estimated a rate of impacts large enough to create craters at least 100 meters deep to be $10^{-13}/km^2$/year. Logan and Berbano (1978) estimated the probability of direct exhumation from a depth of 800 meters for a repository of 10 km^2 to be 1 x 10^{-13}/year. Claiborne and Gera (1974) estimated the probability of exhumation of waste from a depth of

600 meters for a repository of 8 km^2 to be 2×10^{-13}/year. Cranwell et al. (1990) estimated the probability of both direct exhumation of waste from a repository of 8 km^2 at a depth of 630 meters and the fracturing of a shale aquitard at a depth of 400 meters overlying the bedded-salt unit containing the waste. The estimated probabilities are approximately 8×10^{-13}/year and 1×10^{-12}/year, respectively.

Each of these estimated probabilities is substantially below the screening limit of 1×10^{-8}/year (1 chance in 10,000 in 10,000 years) established in the Standard. Based on this screening criterion, meteorite impact can be eliminated from consideration in the WIPP performance assessments.

Erosion/Sedimentation

Both erosion and sedimentation as a result of wind action are ongoing processes throughout the WIPP region. Sand dunes are present at the location of the waste panels, so wind action will result in both processes occurring, although the impact on the performance of the disposal system is likely to be minimal.

No perennial drainage channels are present at the WIPP, and in addition, no intermittent channels are present at the location of the waste panels. Under current climatic conditions, erosion or deposition resulting from surficial-water movement consists of the movement of surficial sand deposits during storms. According to Bachman (1974), the presence and thickness of the Mescalero caliche, which is aerially extensive and approximately 600,000 years old, indicate that the climatic variations since that time have not resulted in significant changes in geomorphic processes.

Because no significantly high topographic features exist in the immediate vicinity of the WIPP, an influx of water-borne sediments that could cover part or all of the WIPP is not physically reasonable. Massive changes to the climatic conditions or tectonic setting within the next 10,000 years that could result in deep erosion at the WIPP are not physically reasonable. A concern about erosion is that the breaching of the Mescalero caliche, which has been interpreted by Bachman (1985) to be a barrier to infiltration of precipitation, could result in recharge elevating the water table, thereby saturating units that are currently unsaturated. According to Swift (1991a), the expected climatic conditions during the next 10,000 years are likely to be within the ranges of conditions that occurred during the past 10,000 years. The past conditions did not result in the formation of major breaches in the Mescalero caliche. Future climatic changes are not expected to cause such breaches. Wetter climatic conditions would result in an increase in the vegetative cover of the area, which could stabilize the current distribution of near-surface sedimentary deposits and protect the caliche.

Both erosion and sedimentation currently are occurring at the WIPP and are certain to occur in the future. Because of this uncertainty, these processes are part of the undisturbed conditions. Neither of these processes will occur to a degree that will affect the performance of the WIPP during the period of regulatory concern. Changes in the rates of these processes to an extent that could affect the performance of the WIPP are not physically reasonable.

Glaciation

No evidence exists to suggest that the northern part of the Delaware Basin has been covered by continental glaciers at any time since the beginning of the Paleozoic Era. During the maximum extent of continental glaciation in the Pleistocene Epoch, glaciers extended into northeastern Kansas at their closest approach to southeastern New Mexico.

According to Swift (1991a), a return to a full glacial cycle within the next 10,000 years is highly unlikely. Based on the extent of previous glaciations and the unlikely prospect that a future glaciation may occur within the period of regulatory concern, glaciation is eliminated as a process for inclusion in WIPP performance assessments based on a lack of physical reasonableness of alterations to the climatic cycle that would result in glaciers reaching or approaching the WIPP.

Pluvial Periods

The purpose of including Pluvial Periods in Table 4-1 was to assure that climatic change is considered in the screening process. Climatic change from current conditions is certain to occur for any location during the next 10,000 years, and as a result, this process has a probability of occurrence of 1.

Based on probability and physical-reasonableness arguments, climatic change is not screened out from consideration in the performance assessment. The effect of climatic change on the groundwater-flow system in the WIPP region has not been determined at this time. As a result, climatic change is retained for performance-assessment analysis.

Because climatic change has a probability of occurrence of 1, this process is considered to be part of the undisturbed performance of the diposal system and is not a separate process for inclusion in the procedure for developing disruptive scenarios.

Sea-Level Variations

Variations in sea level relative to some point on land are the result of the occurrence of other events and processes that have these changes as by-products. Examples are the rise of sea level as a result of glacial melting, which is the result of climatic change, and the uplift of continental areas by crustal rebound after the areas have been deglaciated, which is also the result of climatic change. As a result, sea-level variation is not an independent phenomenon that needs to be considered in scenario development. Another reason for excluding sea-level variation from scenario development is that the WIPP is at an elevation of approximately 3400 feet (1036 meters). No tectonic or climatic process within the next 10,000 years is likely to affect sea level to an extent that would have an effect on the performance of the WIPP.

Hurricanes

Hurricanes are storms that originate over ocean water in the tropics of the northern hemisphere (these storms are called cyclones in the southern hemisphere) and are characterized by high winds and heavy rainfall. Whereas these storms migrate to areas outside of the tropics, the distance of the WIPP from the ocean precludes hurricanes from reaching this location because they dissipate quickly over land.

Whereas hurricanes are not likely to reach the WIPP, intense storms accompanied by heavy rainfall do occur and are certain to occur in the future. These storms are short lived. The effects of these storms on the integrity of the disposal system are likely to be minor. Intense storms are common in southeastern New Mexico, and the effects of individual past storms on the geologic and hydrologic characteristics of the WIPP cannot be distinguished from the long-term geomorphic evolution of the region.

Hurricanes can be eliminated from the performance assessments because the occurrence of these events is not physically reasonable at the location of the WIPP. Intense storms are certain to occur in the future at the WIPP. As a result, intense storms are considered part of normal climate variation and are not included in the development of disruptive scenarios.

Seiches

A seiche is a "free or standing-wave oscillation of the surface of water in an enclosed or semi-enclosed basin...that is initiated chiefly by local changes in atmospheric pressure, aided by winds, tidal currents, and small earthquakes; and that continues, pendulum fashion, for a time after cessation of the originating force" (Bates and Jackson, 1980, p. 568). Seiches range in height from several centimeters to a few meters. Whereas seiches could be of some concern to disposal facilities in certain coastal environments, the distance of the WIPP from ocean basins and other large bodies of water precludes seiches from reaching this location.

Seiches are eliminated from the WIPP performance assessments based on the lack of physical reasonableness of these phenomena at the WIPP location.

Tsunamis

A tsunami is a "gravitational sea wave produced by any large-scale, short-duration disturbance of the ocean floor, principally by a shallow submarine earthquake, but also by submarine earth movement, subsidence, or volcanic eruption" (Bates and Jackson, 1980, p. 668). Because of the elevation of the WIPP and the distance from the oceans, a wave generated by any of the mechanisms mentioned in the definition will not be of a size that could reach the WIPP.

The term tsunami perhaps can be extended to include waves produced by meteorite impacts into bodies of water. Because the WIPP is located in excess of 800 kilometers (500 miles) from the nearest large body of water (e.g., Pacific Ocean) and at an elevation of approximately 1036 meters (3400 feet), a meteorite would have to be large enough and the impact would have to be appropriately located for sufficient energy to move a large enough water volume to inundate all topographic features on the continent between the point of impact and the WIPP. Calculating the size of an appropriately large meteorite is difficult because of the dependence of the calculation on depth of water at the point of impact, water depth along the path toward the WIPP, topographic relief along the path, energy expenditure vaporizing water upon impact, and the mechanical responses of the oceanic sediments and crustal rocks to the impact. The combination of meteorite size and appropriate location makes an impact-generated tsunami reaching the WIPP a low-probability event and perhaps a physically unreasonable event. Changes in sea level caused by the melting of continental glaciers or tectonic activity during the 10,000 years of regulatory concern will not affect this screening decision.

Tsunamis of traditional origin are eliminated from the WIPP performance assessments based on the lack of physical reasonableness of events large enough to generate a wave that could reach the WIPP location. Ocean waves generated by meteorite impacts are eliminated from consideration based on the low probability of the appropriate combination of meteorite size, impact location, and adequate water depth.

Regional Subsidence or Uplift

Regional subsidence or uplift can affect groundwater-flow directions and gradients in addition to affecting erosion and deposition rates and locations. During the geologic history of the WIPP, the region has undergone several periods of regional subsidence and uplift. From early in the Paleozoic Era until approximately 100 million years ago, the stratigraphic record indicates a predominantly marine depositional environment that requires the existence of a subsiding basin in order for nearly 18,000 feet (approximately 5500 meters) of marine sediments to accumulate. The absence of units deposited from Triassic through late Tertiary time indicates either nondeposition or predominantly erosional conditions. Uplift accompanied by erosional conditions are indicated by the fact that rocks of marine origin are present at the WIPP at an elevation of greater than 3000 feet (915 meters). The absence of faults exposed at the surface in the interior of the northern Delaware Basin, which indicates a relatively intact crustal block, the relatively low rate of seismicity, which indicates an absence of or minor tectonic activity, and the wide-spread presence of the Mescalero caliche, which required relatively long-term stable conditions to form, suggest that the interior of the Delaware Basin has been and continues to be relatively stable.

The apparent long-term tectonic stability of the northern Delaware Basin suggests that neither regional subsidence nor uplift is likely to occur in the next 10,000 years on a scale that will alter the geologic or hydrologic systems and affect the performance of the disposal system. For this reason, regional subsidence and uplift do not need to be included in the WIPP performance assessments because of the lack of physical reasonableness of major changes to the tectonic regime within the time period of regulatory concern.

Mass Wasting

Mass wasting is the dislodgement and downslope movement of soil and rock under the direct application of gravitational body stresses (Bates and Jackson, 1980). This process has the potential of affecting the performance of a disposal system by damming surface drainage and impounding water. Impounded water that extends over the disposal system could affect recharge to the underlying units. An impoundment near the disposal system could affect groundwater-flow gradients, thereby altering groundwater-flow patterns.

The Pecos River, which is approximately 24 kilometers (15 miles) at closest approach to the waste panels and more than 90 meters (300 feet) lower in elevation, is the only perennial surface-water drainage feature in the WIPP region. This river is incised, but the resulting valley is not deep enough or steep enough for mass wasting to impound water to a greater depth or aerial extent than currently results from manmade dams. No evidence indicates that past climatic conditions resulted in the existence of other perennial streams that could be dammed by mass wasting. Future climatic conditions are not likely to be substantially different from past conditions.

Because of the sparsity of perennial streams and rivers in the WIPP area and the lack of appropriate morphological features that could result in impoundments, mass wasting is not included in performance assessments for the WIPP based on a lack of physical reasonableness of such events forming large-scale impoundments.

Flooding

Flooding caused by rivers or streams overflowing their banks is a relatively short-term phenomenon. No perennial streams or standing bodies of water are present at the WIPP, and no evidence has been cited that indicates such features existed at this location during or since Pleistocene time (e.g., Powers et al., 1978a,b; Bachman, 1974, 1981, 1987). The Pecos River is approximately 24 kilometers (15 miles) from and more than 90 meters (300 feet) lower than the elevation of the land surface above the waste panels. In Nash Draw, lakes and spoil ponds associated with potash mines are located at elevations 30 meters (100 feet) or more lower than the elevation of the land surface at the location of the waste panels. No evidence has been cited in the literature to support the possibility that Nash Draw was formed by stream erosion or was at any time the location of a large body of standing water.

Because no sources of surface water exist in the WIPP region that could overflow and flood part or all of the WIPP, flooding is not included in the WIPP performance assessments because such events are not physically reasonable at this location.

Diapirism

Because of the relatively low density of salt compared to other sedimentary rocks, bedded-salt deposits at depth have a tendency to rise through and be displaced by higher density overlying rocks. This movement is facilitated by the relatively high ductility of salt when compared to other rock types. Under the appropriate conditions, bedded salt at depth will rise toward the surface and bow the overlying rocks upward, forming a salt anticline. If the overlying rocks are pierced and displaced by the upward movement of the mass of salt, the salt structure is called a salt diapir or salt dome.

The specific conditions that result in diapirism are not known, although some general conditions have been recognized. Based on evidence in German salt basins, Trusheim (1960) concluded that an overburden of 1000 meters (3300 feet) and a salt thickness of at least 300 meters (985 feet) are needed to initiate flow in salt. Similar values are used to locate areas of salt flowage in the Gulf of Mexico (Halbouty, 1979). Other factors that can affect the formation of salt domes are irregularities on the surface of the overburden, variations in the thickness of the overburden, natural variations in the density of the overburden, external stresses (tectonic stresses), depth of burial of the salt, temperature, and geologic setting (Parker and McDowell, 1951, 1955; Gussow, 1968; Trusheim, 1960).

In the northern Delaware Basin, deformation within evaporite units has been noted in disturbed zones along the margin of the Capitan Reef and at isolated locations within the interior of the basin (Borns, 1983; Borns et al., 1983). This deformation is predominantly within the anhydrite and halite of the Castile Formation with weak to nonexistent deformation in the overlying halite of the Salado Formation. Whereas the origin of this deformation is not known, Borns et al. (1983) hypothesized that the mechanism could be either gravity-driven syndepositional deformation, gravity foundering, or gravity sliding. The important thing to note about this deformation is that the thick sequence of bedded salt in the Salado Formation is not deformed. This lack of deformation indicates that the conditions required for salt diapirism to occur are absent in the northern Delaware Basin. Given the long-term stability of this part of the basin, changes in the geologic setting that could initiate diapirism are not likely to occur within the next 10,000 years.

Diapirism is excluded from the WIPP performance assessments because the development of conditions necessary to initiate diapirism are not physically reasonable within the time frame of regulatory concern.

Seismic Activity

Seismic activity refers to earth movement in response to naturally occurring or human-induced events. The most common naturally occurring event that produces earth movement on a regional scale is an earthquake. Examples of other naturally occurring sources are volcanic eruptions, landslides, and meteorite impacts. Human-induced events that can cause seismic activity on a regional scale include but are not limited to fluid extraction and injection, explosions, and rockfalls in mines.

Earthquake records for southern New Mexico date from 1923, and seismic instrumentation started in 1961 (U.S. DOE, 1980a). With the exception of three minor shocks, all shocks felt in the WIPP region prior to 1961 originated from earthquakes more than 100 miles (160 kilometers) from the WIPP and were located to the west and southwest of the WIPP (Sanford and Toppozada, 1974). Since 1961, the distribution of earthquakes remained similar to the distribution before 1961, although a cluster of earthquakes has occurred in the southeasternmost corner of New Mexico and adjacent Texas that may be the result of fluid injection for enhanced oil recovery (Shurbet, 1969). Seismic events occurring within 35 miles (56 kilometers) of the center of the WIPP were recorded in 1972, 1974, and 1978 with the maximum magnitude of 3.6 (U.S. DOE, 1980a). None of these events have been correlated with human activity.

On a seismic risk map of the United States developed for the *Uniform Building Code* (ICBO, 1979), southeastern New Mexico is located in Zone 1, which means that the region has a potential of experiencing seismic activity of Modified Mercalli intensities of V and VI. Seismic activity at these intensities can cause minor damage to some structures. Because the tectonic forces in the southwestern United States and northern Mexico that have produced and continue to produce seismic events are not likely to abruptly change and result in an aseismic region within the next 10,000 years, future regional seismic activity from naturally occurring events is certain to result in ground movement at the WIPP during the 10,000 years of regulatory concern. Ground movement at the WIPP resulting from human-induced events is likely so long as mining and the extraction of energy resources continues. Because ground movement at the WIPP from seismic activity during the next 10,000 years has a probability of occurrence of 1, seismic activity is part of the base-case scenario. No evidence has been cited in the literature of past seismic activity altering either the geologic or hydrologic systems at the WIPP. The alterations of these systems by future seismic activity is not likely to occur. Ground motion caused by seismic activity tends to rapidly dampen with increasing depth (Reiter, 1990), although the precise amount of dampening cannot be reliably predicted (Owen and Scholl, 1981). Because of the depth of the waste panels, the dampening of ground motion with depth, and the low intensity of seismic activity observed and predicted for southeastern New Mexico, future seismic activity will be of no consequence to the performance of the WIPP disposal system.

Volcanic Activity

Volcanic activity refers to magma originating in the lower crust or upper mantle that rises along fracture or fault zones through the overlying rock and is extruded onto the surface. This activity generally occurs in tectonically unstable areas such as rift zones, spreading centers and subduction zones along plate boundaries, and locations above deep-mantle thermal plumes. Volcanic activity is of interest to performance assessments because of the thermal effects of magma on groundwater flow, the possible effects on groundwater flow of volcanic rock of low permeability in fracture or fault zones, and the possible releases of radionuclides to the accessible environment if the magma passes through a disposal facility on the way to the surface.

The Paleozoic and younger stratigraphic sequence within the Delaware Basin is devoid of volcanic rocks (Powers et al., 1978a). Within an area including eastern New Mexico, and northern, central, and western Texas, the closest Tertiary volcanic rocks with notable areal extent or tectonic significance to the WIPP are approximately 170 kilometers (105 miles) to the south in the Davis Mountains volcanic area. The closest Quaternary volcanic rocks are 250 kilometers (155 miles) to the northwest in the Sacramento Mountains. No volcanic rocks are exposed at the surface within the Delaware Basin.

Despite the lack of evidence of past volcanic activity within the Delaware Basin over a time interval of several hundred million years, Logan and Berbano (1978) estimated the probability of volcanism affecting a waste-disposal area of 10 km^2 within this basin to range from 8 x 10^{-12}/year to 8 x 10^{-11}/year. Arthur D. Little, Inc. (1980) estimated this probability to range from 1 x 10^{-10}/year to 1 x 10^{-8}/year. These ranges in probability values are at or below the cutoff probability value for eliminating events and processes from performance assessments. Because of the geologic record and the current geologic setting, a question arises as to whether these probability values are meaningful. No data exist with which to calculate probabilities. With no volcanic rocks within the Paleozoic and younger stratigraphic record, no evidence of exposed volcanic rocks within the Delaware Basin, and a tectonically stable geologic setting, the initiation of volcanic activity within the next 10,000 years is not likely to occur.

Volcanic activity is eliminated from WIPP performance assessments based on the physical unreasonableness of major changes occurring in the tectonic setting of the Delaware Basin within the time frame of regulatory concern.

Magmatic Activity

Magmatic activity as used in this report refers to molten rock (magma) that originates in the lower crust or upper mantle, migrates upward through the crust in response to buoyancy effects or stress/pressure differentials, but cools and crystallizes before reaching the surface. Existing fault or fracture zones may act as pathways for this migration. Magma that cools at considerable depth is referred to as plutonic. Because some of the igneous rocks in southeastern New Mexico and western Texas seem to have cooled relatively close to but not at the surface, all igneous rocks that have cooled before reaching the surface will be referred to as magmatic. This type of activity occurs in tectonically unstable areas. Magmatic activity is of concern to performance assessment because of the possibility that the rising magma could reach a disposal facility, thereby disrupting the engineered barriers designed to isolate the waste, and/or the heat associated with the magma could impose significant thermal effects on groundwater flow.

According to Powers et al. (1978a), no igneous activity has occurred within 100 miles (160 kilometers) of the WIPP since mid-Tertiary time (approximately 30 million years ago). Within the northern Delaware Basin, a northeast-trending lamprophyre dike or series of en-echelon dikes has been identified in outcrop, in boreholes, and by magnetic anomaly. These various sources of information suggest that this dike or dike system is up to 20 feet (6 meters) wide and possibly extends for 80 miles (130 kilometers). Samples from one outcrop location contain vesicles, which indicate emplacement of the dike to relatively shallow depths, although no evidence of extrusion at the surface has been cited. The dike is located as close as 9 miles (14.5 kilometers) to the northwest of the WIPP (Powers et al., 1978a). Age dating of samples of the dike material have produced dates of approximately 30 million years and 35 million years.

Hunter (1989) calculated the probability of a dike of a particular length within the Delaware Basin intersecting a repository to be 2 x 10^{-6} during 10,000 years. This value is lower than the cutoff value of 10^{-4} in 10,000 years established in the Standard. A question arises as to the validity of one of Hunter's assumptions in making this calculation. The probability of another dike intruding into the Delaware Basin was assumed to be the period of regulatory concern (10,000 years) divided by the time interval since the last dike intruded the basin (30 million years). This assumption ignores the tectonic processes that likely contributed to the emplacement of the dike in mid-Tertiary time. Powers et al. (1978a) suggest that the coincidence of the dike's orientation with the orientation of several regional tectonic lineaments in addition to crevasses and fractures in rocks exposed near Carlsbad Caverns, which are approximately 37 miles (59 kilometers) west-southwest of the WIPP, indicates the presence of a zone of crustal weakness. Emplacement of the dike may have been along a fracture zone that formed in the early stages of mid-to-late Tertiary tectonism. Brinster (1991) suggests that uplift of the Guadalupe Mountains, which originated in late Pliocene through early Pleistocene time (Powers et al., 1978a), produced a zone of fractures in nearly the same location and of the same orientation as the dike. Groundwater flow along this fracture zone dissolved salt in the Rustler Formation. Subsidence in response to this salt dissolution produced Nash Draw. Fracturing or faulting occurred in nearly the same location in mid-Tertiary and early Pleistocene times. The fact that igneous material was emplaced along the zone of failure during mid-Tertiary time but not during early Pleistocene time suggests that a change in the geologic processes at this location has occurred. No evidence supports the possibility of a dike being emplaced at the location of the WIPP in any time frame.

In summary, a single dike transected the northern part of the Delaware Basin during the geologic history of this basin. This event occurred approximately 30 million years ago, and a similar event has not occurred in this region since this emplacement. The occurrence of an event that results in the emplacement of another dike at or near the WIPP during the 10,000 years of regulatory concern after 30 million years of quiescence is not physically reasonable. As a result, the recurrence of the tectonic conditions that resulted in magmatic activity is eliminated from the WIPP performance assessments based on the physical unreasonableness of such changes occurring within the time frame of regulatory concern.

Formation of Dissolution Cavities

The circulation of groundwater that is undersaturated with salt can result in the dissolution of salt and the formation of a cavity. Dissolution cavities considered in a demonstration of the scenario-development procedure in Cranwell et al. (1990) were assumed to form by the dissolution of salt from a salt-bearing unit at depth, forming a cavity that resulted in the collapse of the overlying rock units into the cavity. Such debris-filled structures are called breccia pipes or breccia chimneys. In Cranwell et al. (1990), the initiation of dissolution of the salt resulted from the fracturing of an aquitard either above or below the waste panels and the flow of undersaturated groundwater through the fractures. Disruption of the unit overlying the salt has the potential of providing a pathway for groundwater to dissolve and remove the salt and eventually reach the radioactive waste, whereas disruption of the underlying unit has the potential of the waste itself being involved in the collapse into the underlying cavity where circulating groundwater could have access to disrupted waste. In addition to the formation of breccia chimneys by similar processes in the WIPP region, the possible migration of a dissolution front from Nash Draw toward the WIPP also is considered in this section.

Deep Dissolution

Hunter (1989) dismissed the formation of deep dissolution cavities using the screening criterion of low probability. Several of the assumptions used to calculate the probability cannot be justified. For this reason, an alternate approach is used to screen the formation of deep dissolution cavities. Anderson (1978, 1981, 1983) proposed that salt dissolution at depth is a major contributor to the total amount of salt removed from within the northern Delaware Basin. Davies (1983) proposed that groundwater circulating through higher-conductivity zones in the Bell Canyon Formation has resulted in at least local areas of deep salt dissolution in the interior of the basin. Using regional well-log correlations, Borns and Shaffer (1985) concluded that the geologic features both Anderson and Davies had attributed to deep salt dissolution were more readily attributed to mass redistribution in the Castile Formation, the presence of localized depocenters in the lower Castile Formation that resulted in the deposition of thicker upper Castile and lower Salado sediments, and topographic irregularities on the top of the Bell Canyon Formation producing apparent deformational structures in the overlying units.

In the northern Delaware Basin, field work and drilling have confirmed the existence of two breccia chimneys and suggested the existence of two more. Stratigraphic relationships and active subsidence within San Simon Sink indicate that dissolution has been an ongoing process at this location (Nicholson and Clebsch, 1961; Lambert, 1983). All of the confirmed and suspected breccia chimneys and San Simon Sink are located over the Capitan Reef (Lambert, 1983). According to Snyder and Gard (1982), the origin of Hill A, which is located approximately 30 kilometers (17 miles) east-northeast of Carlsbad, is the result of dissolution of the Capitan Limestone at depth, collapse of the Salado and younger formations into the dissolution cavity, and dissolution of Salado and Rustler salts in the down-dropped blocks within the chimney, possibly by downward-moving water. The association of the other chimneys and San Simon Sink with the location of the buried Capitan Reef suggests that deep dissolution only occurs where groundwater circulates within the reef and where rocks containing evaporite minerals have collapsed into cavities within the reef.

Breccia chimneys and buried reefs have not been identified within the interior of the Delaware Basin. Based on the association of known chimneys and reefs, the deep dissolution that produces breccia chimneys is not physically reasonable at or near the WIPP.

Shallow Dissolution

Whereas deep dissolution involves processes occurring in the lower Salado and deeper formations, shallow dissolution involves processes that can affect the upper Salado and shallower formations. Shallow dissolution has the potential of occurring as a result of vertical recharge from the surface, horizontal flow along the contact zone between the Salado and Rustler Formations, and migration of the dissolution front from Nash Draw toward the WIPP. Each type of dissolution has the potential of disrupting the Rustler Formation to an extent that groundwater flow in the Rustler Formation is changed from confined to unconfined conditions. A change in groundwater-flow conditions could have an important impact on the lengths of flow paths and the rate of groundwater flow.

In the subsurface at the WIPP, the shallowest unit that is composed of a significant soluble component is the Forty-niner Member of the Rustler Formation. With the exception of isolated sandstone lenses in the Dewey Lake Red Beds, the units overlying the Forty-niner Member are not saturated (Mercer, 1983; Brinster, 1991). The thickness of the units overlying the Rustler Formation range from approximately 80 meters (260 feet) at the western boundary of the WIPP to approximately 200 meters (650 feet) at the eastern boundary (Brinster, 1991). Tests to determine the hydrologic properties of the lower portion of the Dewey Lake Red Beds had to be stopped because of the low water content and permeability of the rocks (Beauheim, 1986, 1987a). In order for rainfall to reach the Forty-niner Member to dissolve the halite component, this water must infiltrate through the surficial wind-blown deposits and sandy Berino paleosol. Beneath the sandy material, the water must pass through the dense and generally massive, although locally fractured, Mescalero caliche. Between the caliche and the Forty-niner Member lie the sands and clays of the lower Dockum Formation and 75 to more than 150 meters (245 to 490 feet) of the Dewey Lake Red Beds. Because of the low permeability of the lower portions of the Dewey Lake Red Beds, the brine will have an extremely low flow rate, thereby blocking additional infiltrating water from reaching and dissolving the salts in the Rustler Formation. Because of the presence of both geologic and hydrologic constraints on infiltration and groundwater flow, dissolution of salt by infiltrating water at the WIPP, if this process can occur at all, will have a low consequence on the hydrologic behavior of the disposal system. Because of low consequence, this process can be eliminated from the performance assessment of the WIPP.

A layer of material is present at the contact of the Salado and Rustler Formations that has been interpreted as insoluble residue left after the dissolution of salt primarily of the Salado Formation (Robinson and Lang, 1938; Mercer and Orr, 1977; Mercer, 1983). This layer is referred to as the Salado-Rustler contact residuum. The contact residuum extends from at least the central portion of Nash Draw, across the WIPP, and into western Lea County. Based on currently available data, the thickness of the contact residuum within the WIPP ranges from 7 to 36 meters (23 to 118 feet) (Mercer, 1983; Lappin et al., 1989). Groundwater flow within the residuum is from an unidentified recharge area, north to south across the WIPP, and then to the southwest to the Pecos River (Mercer, 1983). Although the water-chemistry data compiled in Lappin et al. (1989) do not indicate a trend in increasing or decreasing total dissolved solids (TDS) or water density in the vicinity of the WIPP, Brinster (1991) states that the brine concentration generally becomes greater to the southwest and the groundwater is nearly saturated in the portion of Nash Draw near the Pecos River. An increase in fluid density in the direction of flow indicates that dissolution of the adjacent salt is continuing, although the hydraulic properties of the residuum suggest that groundwater flow within this unit is relatively slow, and the water-chemistry data suggest little dissolution is occurring at the WIPP. Because dissolution has occurred along the Salado-Rustler contact in the past, is currently taking place to some degree, and is likely to continue into the future, this process is part of the base-case scenario. The units that overlie the contact residuum (especially the relatively brittle Mescalero caliche) in the immediate vicinity of the WIPP have not been noticeably disrupted by this dissolution process, except along the margin of Nash Draw (U.S. DOE, 1980a). In addition, the mechanically brittle anhydrite layers in the Rustler Formation tend to be unfractured. Because this long-term dissolution process seems to have had a minimal impact at the WIPP, this process is not likely to have a significant effect on the performance of the disposal system.

Nash Draw was formed by the dissolution of evaporite minerals in the Rustler and upper Salado Formations (Bachman, 1981; Lambert, 1983; Brinster, 1991). Interpretations differ as to the duration of this dissolution. Bachman (1974) estimated that Nash Draw began to form since the development of the Mescalero caliche 510,000 years ago (Bachman, 1985) and is continuing at present, although the rate of dissolution has not been a constant because of variations in the climate. With climatic conditions in southeastern New Mexico in a drying trend since the Pleistocene Epoch, the rate of dissolution has been decreasing. Brinster (1991) concluded in his synthesis of the regional geohydrology that a fracture system developed at the location of Nash Draw in association with the uplift of the Guadalupe Mountains, which is in the same time frame as the estimated age of uplift by Bachman (1974). Recharge during wetter climatic conditions and groundwater from the overlying units drained through this fracture system, dissolving the evaporite minerals and resulting in the collapse of the overlying units. Drainage of groundwater from the overlying units allowed dissolution to continue during drier climatic conditions. Once the groundwater drained from the overlying units, the dissolution process that formed Nash Draw stopped from a practical point of view. By this interpretation, the dissolution that formed Nash Draw was a relatively short-lived process that is not continuing at present. A change to a much wetter climate presumably could result in a limited resumption of dissolution, although at lower rates than during the formation of Nash Draw.

If Bachman's (1974) interpretation of the origins of Nash Draw is correct, Nash Draw is continuing to expand in width. At the closest point to the WIPP, Nash Draw is approximately 6.4 kilometers (4 miles) wide. If Nash Draw did originate 510,000 years ago and the process is continuing, the mean rate of expansion has been 0.01 meters/year (0.4 inches/year). With symmetrical expansion from the axis of the draw, the rate of expansion toward the WIPP is half of this value, or 0.005 meters/year (0.2 inches/year). Assuming that climatic change to wetter conditions can extend this rate of expansion for the next 10,000 years, the margin of Nash Draw would be approximately 50 meters (164 feet) closer to the WIPP than the present location. With the WIPP located approximately 6.4 kilometers (4 miles) from Nash Draw, the presence of Nash Draw is unlikely to affect the performance of the disposal system. A ten-fold increase in this mean rate of expansion would result in the margin of Nash Draw being 500 meters (1640 feet) closer to the WIPP than the present location, although a climatic change of a magnitude that would produce such an increase in the rate of expansion in the relatively short time frame of 10,000 years is not physically reasonable.

If Brinster's (1991) interpretation is correct, the expansion of Nash Draw from the present location to the WIPP by dissolution is not a physically reasonable process within the time frame of regulatory concern, because the primary source of water for the dissolution of evaporites was groundwater whose source has, for practical purposes, been depleted.

Summary of Screening of Dissolution

Based on the geologic setting of confirmed and likely breccia chimneys and the lack of compelling field evidence of deep dissolution that could result in the formation of breccia chimneys at or near the WIPP, processes that could result in deep dissolution affecting the WIPP are not physically reasonable. Of the possible processes that could result in shallow dissolution, dissolution along the contact of the Salado and Rustler Formations is an ongoing process. This process is part of the undisturbed performance of the disposal system. The rate of dissolution within this zone is slow enough that no significant changes will occur to the groundwater-flow system during the time period of regulatory concern. Dissolution that could result in the margin of Nash Draw reaching the WIPP within the time frame of interest is not physically reasonable.

Formation of Interconnected Fracture Systems

Fracture systems do not spontaneously occur but instead are the product of the occurrence of events or processes. If an event or process produces fractures, the effects of these fractures on the hydrologic properties of the disposal system should be included in consequence modeling as an alteration or modification of base-case conditions. An originating event or process may be appropriate for inclusion in scenario development, whereas the inclusion of fracture systems, which are produced by events and processes, is not. No tectonic processes are occurring in the northern Delaware Basin at a rate that would produce new fracture systems in rocks in the WIPP area within the time frame of regulatory concern.

Faulting

Faulting refers to either the creation of a new fault or renewed movement on an existing fault. The creation of a new fault is of concern to performance assessment because of the potential for the fault to pass through the disposal facility and rupture waste containers and possibly engineered barriers to groundwater flow. In addition, new faults may provide new pathways for groundwater flow or divert flow to alternate pathways. Reactivation of existing faults may modify hydraulic properties along existing pathways of groundwater flow and possibly redirect groundwater flow to alternate pathways. Modifications to existing pathways or the creation of new pathways may affect the travel time of radionuclides transported by groundwater to reach the accessible environment.

Structure-contour maps for several major units in the WIPP vicinity (Powers et al., 1978a) indicate that sedimentary units older than the Salado Formation are faulted and the Salado Formation and younger units are not. Although this change in the occurrence of faults coincides with a change in the construction of the maps from seismic-reflection data to borehole data, the quantity and spacing of the borehole data suggests that the absence of faults in the Salado and younger units is real. In addition, no tectonic fault scarps have been identified within the interior of the northern Delaware Basin. As discussed in the previous section on "Magmatic Activity," the lamprophyre dike and Nash Draw may be located along a long-lived zone of crustal weakness. The relatively undisturbed nature of the brittle rocks of the Rustler Formation indicates that this zone of weakness does not extend to the WIPP.

Movement on faults typically occurs along existing faults in tectonically active areas, and the formation of a new fault that is not subsidiary to an existing fault within such areas is a rare event (Bonilla, 1979). At the WIPP study area, faults are present in rock units older than the Salado Formation (Powers et al., 1978a). The lack of evidence for the existence of faults within the Salado Formation and younger units and the low seismic activity within the northern Delaware Basin indicate that the tectonic setting has not been suitable for faulting to occur since at least the end of Permian time 245 million years ago.

Faulting as a result of tectonic activity is excluded from the WIPP performance assessment because the establishment of tectonic conditions that would result in faulting in the vicinity of the WIPP is not physically reasonable in the time frame of regulatory concern.

4.1.4 EVALUATION OF HUMAN-INDUCED EVENTS AND PROCESSES

In addition to the three screening criteria proposed by Cranwell et al. (1990), Appendix B of the Standard limits the severity of human intrusion at the location of the waste panels that need to be included in the performance assessments. As stated in Appendix B, "...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" (U.S. EPA, 1985, p. 38089). The Standard does not specifically define the term "severe" as used in Appendix B, but the preamble to the Standard does provide guidance as to the intent of the EPA. According to the preamble,

> The implementing agencies are responsible for selecting the specific information to be used in these [including the limiting assumptions regarding the frequency and severity of inadvertent human intrusion] and other aspects of performance assessments to determine compliance with 40 CFR Part 191. However, the Agency [EPA] believes it is important that the assumptions used by the implementing agencies are compatible with those used by 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).

In calculating population risks as background in developing the Standard, Smith et al. (1982) considered exploratory drilling as the only realistic mode of human intrusion into the waste-storage facility. Following the example set by the EPA, exploratory drilling is the only mode of human intrusion within the boundaries of the waste panels that will be included in the performance assessments of the WIPP.

Explosions

Human-induced explosions are a concern to the WIPP performance assessment, because this type of event has the potential of breaching the engineered barriers and/or introducing disruptions to the geologic and hydrologic systems. These disruptions could alter the groundwater-flow path within the disposal system and provide shorter pathways for radionuclides to reach the accessible environment. Possible explosions associated with nuclear criticality are considered in a separate section.

Based on the current level of technology, the only type of human-induced explosion that has the potential of significantly impacting the performance of the disposal system is nuclear in origin. The deliberate use of a nuclear device to disrupt the disposal system or exhume waste would not be included in the WIPP performance assessment because Appendix B of the Standard limits the human-intrusion events that need to be considered to those that are inadvertent.

Inadvertent explosions at the location of the waste panels also can be excluded from the WIPP performance assessments. Appendix B of the Standard limits the severity of human intrusion at the location of the repository that must be considered in performance assessments to exploratory drilling for resources. Explosions away from the location of the waste panels that potentially could result in the inadvertent disruption of the disposal system include surface or near-surface bomb detonations during war, underground testing of nuclear devices, and underground detonation of nuclear devices for peaceful purposes.

The possibility of surface or near-surface detonation of nuclear bombs during warfare requires that nations maintain nuclear arsenals into the future, a war takes place that involves nuclear weapons, and either a strategic facility worth targeting by an enemy exists in the WIPP region or the delivery system malfunctions or is damaged, causing the nontargeted area of the WIPP region to be hit. Surface nuclear detonations may affect hydrologic systems by a combination of cratering and seismic waves, whereas the effects of a near-surface detonation will primarily be the result of seismic waves. The effects of an explosion on the disposal system will be greater the closer the explosion occurs to the WIPP, but the closer an explosion occurs, the lower the probability of the occurrence because of the progressively smaller area surrounding the WIPP. Seismic effects on the source term or the disposal system are likely to be addressed within parameter uncertainty during modeling. Nuclear explosions in the WIPP region during warfare that could have significant effects on disposal-system performance are low-probability events.

The topic of future nuclear testing presumes that future societies will continue to possess nuclear devices that require testing. For this discussion, future nuclear testing is assumed to require a large area with isolation similar to the Nevada Test Site. Whereas the conditions of size and isolation are met in the northern Delaware Basin at present, future uses of this region are not known. If underground testing is conducted in the Delaware Basin, tests presumably would occur in the bedded salt of the Salado Formation because of the lack of fractures within this unit and the ability of salt to heal fractures generated during testing. The size of nuclear devices tested would have to be relatively small in order to assure that the low-permeability units that impede dissolution of the Salado Formation are not ruptured. Questions arise as to whether salt would be suitable for nuclear testing given the high potential for compromising the test site by salt dissolution, and the selection of the northern Delaware Basin instead of other areas considering the vast areas of the continental United States that are underlain by bedded salt. The consequences of testing are likely to be limited to seismic effects on permeabilities of hydrologic units and premature rupturing of waste drums and containers. Both of these effects can be addressed with parameter uncertainties during performance modeling, although selection of the northern Delaware Basin for a future test site has a low probability, considering the numerous other locations and options for testing.

Nuclear explosions have the potential of providing a technique for fracturing oil- and natural-gas-bearing units to enhance resource recovery. Future societies may use this technique or evaluate the use of non-nuclear explosions as hydrocarbon resources become depleted. The size of explosions will be relatively small in order to maximize fracturing of the unit being exploited instead of maximizing cavity size or fracturing the surrounding rocks, which could allow the hydrocarbons to escape. In the area surrounding the WIPP, the stratigraphic units with the highest resource potential tend to be thousands of meters deeper than the waste panels. Disruptions to the WIPP disposal system and modification of the source term resulting from explosions at depth are likely to be minor to nonexistent.

Nuclear or other large-scale explosions at the location of the waste panels can be excluded from performance assessments, because these explosions would be more severe than required by the Standard for inclusion in these assessments. Accidental surface and near-surface nuclear explosions during warfare can be excluded from the assessments on the basis of low probability. Nuclear testing and/or the use of nuclear devices for enhanced resource recovery are highly speculative future human activities. The combination of the likelihood that these activities will occur in the future at a location and be of a magnitude that will affect the WIPP disposal system has a sufficiently low probability to eliminate such events from scenario development.

Drilling

Appendix B of the Standard restricts the type of drilling that needs to be included in performance assessments to exploratory drilling for resources. This restriction eliminates from consideration the higher drilling densities associated with the development of resource deposits. This appendix also discusses the frequency of exploratory drilling. In the section on Institutional Controls, the Standard states that "...the Agency [EPA] believes that passive institutional controls can never be assumed to eliminate the chance of inadvertent and intermittent human intrusion into these disposal sites" (U.S. EPA, 1985, p. 38088). This statement is interpreted here to require the probability of exploratory drilling by at least one borehole to be greater than the cutoff established in the Standard (i.e., greater than 1 chance in 10,000 in 10,000 years). In the section of Appendix B entitled "Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories," the statement is made that "...the Agency [EPA] assumes that the likelihood of such inadvertent and intermittent drilling in 10,000 years 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..." (U.S. EPA, 1985, p. 38089). This statement provides an upper limit on the drilling density in 10,000 years for consideration in performance assessments. The preamble to the Standard does provide an option for the use of other drilling densities by including the following statement:

> The Agency [EPA] believes that performance assessments should consider the possibilities of such intrusion, but that limits should be placed on the severity of the assumptions used to make the assessments. Appendix B to the final rule describes a set of parameters about the likelihood and consequences of inadvertent intrusion that the Agency assumed were the most pessimistic that would be reasonable in making performance assessments. The implementing agencies may adopt these assumptions or develop similar ones of their own (U.S. EPA, 1985, p. 38077).

With 30 boreholes/km^2 in 10,000 years as a "worst-case" assumption, the implication of the above statement is that the implementing agencies should strongly consider developing site-specific drilling densities. For the WIPP performance assessment, a panel of experts with a broad spectrum of backgrounds was convened to propose possible modes of inadvertent human intrusion at the WIPP during the next 10,000 years (Hora et al., 1991). Topics addressed by the panel included drilling densities and time frames of resource exploration for various possible future states of civilization. Each of the four teams within the panel estimated future drilling densities substantially lower than 30 boreholes/km^2 in 10,000 years.

Because of the wording of the Standard, exploratory drilling for resources is retained for inclusion in performance assessments. Exploratory drilling can be subdivided to identify more than one event to facilitate computer modeling and both consequence and sensitivity analyses.

Based on economic conditions and resource demands at the time of geological characterization, potash and natural gas were identified as the only two resources with economic potential at the WIPP (Powers et al., 1978b). The McNutt Potash Member of the Salado Formation, which is approximately 400 feet (120 meters) above the depth of the proposed waste panels (Nowak et al., 1990), is the only unit in the stratigraphic sequence in the northern Delaware Basin with potash in economic quantities, although economically recoverable potash is not present in this unit at all locations (Brausch et al., 1982). Keesey (1976, 1979) concluded that the Morrow

Formation at a depth in excess of 11,600 feet (3550 meters) beneath the waste panels is the only reasonable target for resource exploration for natural gas and that crude oil would not be reasonably extractable from any unit at this location. Depending on the resource needs of future societies, all exploratory drilling could be shallower than the waste panels if the target resource is potash, all exploratory drilling could be deeper than the waste panels if the target resource is natural gas, or drilling could be divided in any ratio between the two depths if both resources are targets.

Mining

During geological characterization of the WIPP location (Powers et al., 1978a,b), each of eight natural resources were evaluated for their potential occurrence in economic quantities at the WIPP. The resources investigated were caliche, gypsum, salt, uranium, sulfur, lithium, potash, and hydrocarbons. Uranium was not found to be present in even marginally economic quantities. Sulfur deposits have not been identified in the northern Delaware Basin. Lithium had been reported in marginally economic quantities in samples from a single brine reservoir, but Powers et al. (1978b) did not consider lithium as a potential resource at the WIPP because of a lack of evidence that brine of an appropriate composition and quantity exists at this location. Caliche, gypsum, and salt were not considered to be economical at the WIPP because of their widespread occurrence and the existence of more easily accessible deposits elsewhere in the region. Crude oil was not considered to be available in sufficient quantity to qualify as a potentially economically viable resource. Only natural gas and potash were concluded to be potentially exploitable resources.

Bedded-salt deposits also have the potential of being mined to form cavities for natural-gas storage. Guidance in the Standard excludes consideration of mining of storage facilities at the WIPP, because mining is a more severe disruption of the disposal system than exploratory drilling for resources. Outside the boundary of the WIPP, mining cavities for natural-gas storage can be evaluated in the same way that Powers et al. (1978b) evaluated mining salt. The existence of extensive areas underlain by bedded salt substantially reduces the likelihood of cavities being mined in the immediate vicinity of the WIPP.

Of the two potential resources at the WIPP identified in Powers et al. (1978b), potash must be recovered by mining. Langbeinite is the primary mineral mined for potash. Conventional mining currently is active in the region around the WIPP. Based on the physical properties of langbeinite, the characteristics of the ore deposits, and the limited availability of suitable water, Brausch et al. (1982) concluded that solution mining is not feasible in this area.

The Standard excludes mining of any type at the location of the waste panels from inclusion in scenarios for performance assessments. If mining beyond the boundaries of the WIPP affects the disposal system, mining needs to be included in scenario development. Brausch et al. (1982) noted that subsidence commonly occurs over potash mines in the WIPP region, although no incidence of water leaking into the mines from overlying units has been observed. Subsidence over a mine has the potential of forming a catchment basin where runoff can accumulate (Guzowski, 1990). If the underlying units are sufficiently fractured by the subsidence, accumulated water may have a pathway to recharge these underlying units. In the WIPP region, this type of recharge has the potential of affecting groundwater flow in members of the Rustler Formation at the WIPP and/or adding water to what is now the unsaturated zone.

Whether or not potash in southeastern New Mexico will continue to be mined in the long-term future is not known. The probability of future mining is assumed to be above the cutoff established in the Standard. Effects of subsidence on recharge and groundwater flow also are not known, although computer modeling by the WIPP Performance Assessment Division is in progress to estimate these effects. For preliminary scenario development, potash mining beyond the area of the waste panels is retained.

Injection Wells

Injection wells refers to the drilling of wells followed by injection of fluid. This fluid can either be water (e.g., water produced during the exploitation of resources or water injected to enhance hydrocarbon recovery) or hazardous liquids (e.g., byproducts of chemical industries). Injection wells are of interest to performance assessment because a waste-filled room or drift may be encountered during the drilling process, thereby providing a mechanism for transporting waste to the surface, an abandoned well could create a new pathway for groundwater after the well is abandoned, and the injection of a sufficient quantity of liquid may change the potentiometric field for the groundwater.

Saturated sedimentary units within a basin can be underpressured (below hydrostatic) if the basin is topographically tilted and capped by a thick sequence of low-permeability rocks (Belitz and Bredehoeft, 1988). A preliminary examination of well data for the northern Delaware Basin by Brinster (1991) found that units between the base of the Castile Formation and a depth of 1,800 meters (approximately 6,000 feet) are underpressured. Units deeper than 1,800 meters also are underpressured except where natural-gas reservoirs are present.

Whether fluid injection for any reason is a possible future event depends on the technological status and societal attitudes of future civilizations, as well as the hydrogeologic suitability of units at depth at a particular location. Although the deeper units in the basin tend to be underpressured, pressures associated with natural-gas production from deep units in the Delaware Basin tend to be greater than hydrostatic (Lambert and Mercer, 1978). Deep units beneath the WIPP have been identified as potentially containing hydrocarbon resources with natural gas possibly being present in economic quantities (Powers et al., 1978b). The presence of natural-gas reservoirs in units beneath the WIPP would limit or possibly eliminate the availability of underpressured units for injection of fluid at this location.

Unless the location of the waste panels has some uniquely favorable characteristics for injection wells that are currently not recognized, the selection of this location, which consists of an area of approximately 0.5 km^2 (0.2 mi^2), seems to be an unlikely event considering the area of the basin (33,000 km^2 (12,470 mi^2)) and the area of the region as a whole where injection wells could be located. A qualitative assessment of this location being chosen suggests that the probability is low but not positively less than the cutoff value provided in the Standard.

A borehole being drilled for an injection well could penetrate a waste-filled room or drift and possibly a brine reservoir in the Castile Formation. If the assumption is made that the geologic characteristics of the deep formations beneath the WIPP have hydrologic characteristics acceptable for injection wells, both intercepting a room or drift and/or a brine reservoir are physically reasonable. The effects of either occurrence on the performance assessment of the WIPP would be approximately the same as deep resource-exploration boreholes. For injection wells, more care might be taken in the emplacement of seals, because the use and abandonment of injection wells tend to be less routine than for oil and gas exploration boreholes.

The effects of injection wells on groundwater flow in units shallower than the Salado Formation is likely to be negligible. Units selected for injection will be thousands of feet deeper than the Rustler Formation, which is the most likely path for the groundwater transport of radionuclides to the accessible environment. The low-permeability Bell Canyon, Castile, and Salado Formations are approximately 4,000 feet (1,220 meters) thick at the WIPP (Powers et al., 1978a), and these low-permeability units will isolate the groundwater flow in the Rustler Formation from the pressure increases in the much deeper units caused by the injection of fluids.

The emplacement of injection wells cannot be immediately eliminated from consideration on the basis of probability of occurrence, although the locations at which such wells are drilled are limited by restrictions in the Standard. Appendix B of the Standard states that the intruder's own exploration procedures will soon detect that the drilling activity is not compatible with the area. Because the candidate hydrologic units for injection are substantially deeper than the waste panels, a well being drilled for injection that penetrates a waste-filled room or drift will not be drilled for additional thousands of meters to an injectable unit if the driller soon detects the incompatibility of the area with injection.

Injection wells can be eliminated from consideration in performance assessments because of a lack of consequence. Because the units suitable for injection are separated from the waste panels and hydrologic units above the panels by the virtually impermeable evaporite sequences of the Castile and Salado Formations, the injection of fluid (e.g., brine associated with natural-gas production) at depth will have no effect on the disposal system.

Withdrawal Wells

Withdrawal wells refer to boreholes drilled and completed for the extraction of groundwater, oil, or natural gas. Wells withdrawing groundwater have the potential of altering the flow gradient in the area surrounding a well or of altering the flow on a larger scale if water is withdrawn by a field of wells. Water wells also have the potential of providing an alternate pathway for radionuclides to reach the accessible environment if the unit being pumped contains radionuclides that have escaped from the waste-filled rooms and drifts. Because the Standard restricts the severity of drilling that needs to be included in performance assessments of the WIPP to exploratory drilling for resources, oil or gas production wells, which are withdrawal wells, only need to be considered in areas outside of the repository area. Areas where oil or gas are withdrawn have the potential of surface subsidence in response to the removal of the confined fluid that supports some of the weight of the overburden.

Water Wells

Water-producing units above the Salado Formation are restricted to the Culebra Dolomite and Magenta Dolomite Members of the Rustler Formations, although the yield of the Magenta Dolomite is so low that the unit generally receives little attention (Brinster, 1991). Little is known of the specific hydrologic properties of the units deeper than the Salado Formation at the WIPP, but with the exception of possible brine reservoirs in the Castile Formation, water-producing units beneath the Salado Formation are in excess of 5,000 feet (1,500 meters) deep at this location. Because of the considerable depth to the deeper water-producing units, only the Culebra

Dolomite is regarded as a realistic candidate for water usage in this screening of events and processes.

One of the requirements for a "significant source" of groundwater as defined in the Standard is a total-dissolved-solids (TDS) content of less than 10,000 mg/ℓ, which has been used as the upper TDS limit to potable water for both people and cattle (Lappin et al., 1989). Based on the 10,000 mg/ℓ-TDS limit, no potable groundwater has been identified in the Culebra Dolomite within the land-withdrawal boundaries of the WIPP (Lappin et al., 1989). In the *Final Supplemental Environmental Impact Statement* (U.S. DOE, 1990c), no potable water was projected to occur within 5 kilometers (3.1 miles) of the waste panels. A possible exception to this TDS distribution is one of four water samples taken from well H-2 at different times. One sample had a TDS of 8,900 mg/ℓ, whereas the other three samples taken at later times ranged from 11,000 to 13,000 mg/ℓ (Lappin et al., 1989). An explanation of these changes in TDS content for the water from this well has not been verified, nor has the reason been determined for the anomalously low TDS content of the water for this particular location.

Whereas a lack of potable water within 5 kilometers of the waste panels would seem to eliminate the emplacement of water wells from scenario analyses, other considerations require that this event be retained for further evaluation. Most of the groundwater in the Culebra Dolomite is substantially more saline than seawater. At some locations (e.g., H-1, H-2, H-4, H-14, P-15), the TDS content of the water may be suitable for some types of fish or shrimp farming if the sustained yield of the Culebra Dolomite is large enough to supply such an operation. Cones of depression from pumping wells at these locations could alter the groundwater-flow pattern in the dolomite and increase the rate of groundwater flow or alter the pathway to the accessible environment.

Oil and Gas Wells

The Standard limits the severity of human intrusion at the waste panels to exploratory boreholes. Oil and gas withdrawal wells would be associated with production rather than exploration. Withdrawal wells at oil or gas fields at a distance from the waste panels need to be considered for their possible effects on the groundwater-flow system, especially those effects from subsidence that result in fracturing of shallow units and enhanced recharge.

Resource evaluation of the WIPP region was part of site characterization. Natural gas in the Morrow Formation was concluded to be the only possible hydrocarbon resource with economic potential in the area (Keesey, 1976, 1979). At the WIPP, the Morrow Formation is at a depth in excess of 13,000 feet (3,960 meters) (Powers et al., 1978a). Because of the depth and rigidity of the possible production horizons, subsidence would not be expected to occur if gas (if present) was removed (Brausch et al., 1982).

Geothermal Wells

An assessment of the geothermal potential of the United States (Muffler, 1979) identified no potential geothermal resources in southeastern New Mexico. This conclusion was based on the lack of thermal springs and the relatively low heat flow measured in boreholes in this region.

Because favorable geothermal conditions do not exist in the northern Delaware Basin and significant changes in the geothermal regime within the time frame of regulatory concern are not physically reasonable, the drilling of geothermal wells is excluded from scenario development.

Summary of Withdrawal Wells

Poor water quality at and near the WIPP precludes the emplacement of water wells for domestic or livestock use. Depending on the tolerable water quality and sustainable water needs for fish or shrimp farming, emplacement of water wells into the Culebra Dolomite may be a realistic consideration for performance assessment because of possible alteration of the groundwater-flow field. Emplacement of water wells is retained for further evaluation and is designated Event E3.

Withdrawal of natural gas from deep reservoirs typically does not result in subsidence of the overlying units. Without subsidence, natural-gas withdrawal wells outside the boundaries of the WIPP will not affect the disposal system. This type of withdrawal well can be eliminated from consideration in the WIPP performance assessments because of low consequence. The EPA guidance for implementation of the Standard states that human intrusion at the location of the waste panels with consequences more severe than exploratory drilling for resources need not be considered. Gas-production wells at this location can be eliminated from consideration based on regulatory restriction.

Irrigation

Irrigation uses water from rivers, lakes, impoundments, and/or wells to supplement the rainfall in an area to grow crops. The amount of water needed depends on the type of crop, the amount, timing, and distribution of naturally occurring precipitation, the amount of evapotranspiration, and the type of soil or sediments being irrigated. Irrigation is of interest to performance assessment because of the possibility that the water added to the surface will infiltrate and reach the water table, possibly affecting groundwater flow and the transport of radionuclides.

In Eddy County, irrigation of the Pecos River valley began in 1887 using water from both the river and wells (Pasztor, 1991). At present, agricultural activity in this region is restricted to areas near the Pecos and Black Rivers where water is available from either impoundments or from shallow wells in the alluvial aquifers near the rivers (Hunter, 1985).

Two major obstacles exist to the use of irrigation at the WIPP. One is the poor quality of the soil. Nearly the entire area of the WIPP is covered by stabilized sand dunes that can be as much as 100 feet (30 meters) thick (Powers et al., 1978a). Beneath these sand dunes is the Berino paleosol, which consists of up to 1.5 feet (0.4 meters) of argillaceous sand. Underlying this unit is up to 10 feet (3 meters) of the Mescalero caliche, which is a well-cemented calcareous paleosol. Any attempt at agricultural development at this location would require considerable soil modification. The other problem is the supply of water in both the quantity and quality required for crops. Water quality may be less of a concern in the future as more salt-tolerant crops are identified and developed (Gibbons, 1990), although a salt content equivalent to seawater seems to be an upper limit for most naturally occurring plants. Sources of water capable of long-term yield are few in number in the WIPP region, and the sources that do exist generally are already committed (e.g., the Pecos River) and/or are being mined and are likely to be depleted (e.g., the Capitan Limestone). Geologic units deeper than the Bell Canyon Formation are possible new sources of water for irrigation, although the several thousand foot depth to these units is considerable for irrigation wells, the amount of water available is not known, and the salinity of the water is likely to be high.

The WIPP is a relatively small area within the southeastern portion of New Mexico. By the time of the assumed loss of active institutional controls 100 years after closure of the WIPP, population pressures for more water should be intense. If technological breakthroughs have occurred and desalination is economically feasible for irrigation, vast areas of southeastern New Mexico and West Texas will be available for agricultural uses. Even with desalination, water supplies are limited in the region. The land available for irrigation is likely to outstrip the available water. As a result of limited water supplies, areas with better soils will be the primary candidates for irrigation (Swift, 1991b). Additional land at the WIPP with poor soil is unlikely to divert water from committed uses. If large-scale desalination does not develop, no uncommitted water is likely to be available to irrigate a newly available area with poor soil.

Irrigation at the WIPP is not included in the performance assessments because of the low probability of the combination of factors and necessary conditions required for this activity to be feasible.

Damming of Streams and Rivers

Damming refers to the building of a barrier across a topographically low area in order to impound water. As with mass wasting, impoundments have the potential of affecting the performance of the disposal system by altering recharge if the impoundment extends over the disposal system or by altering the groundwater gradients if the impoundment is near the disposal system.

In the WIPP area, only two topographically low features are of sufficient size to warrent consideration for damming. These features are the Pecos River and Nash Draw. During Pleistocene time, the Pecos River migrated to its present position and became incised. According to Brinster (1991), as the climate became drier and the hydraulic heads in the Capitan Reef became lower, the overall flow in the river decreased to the point where the river now has a small bed load and does little if any downward erosion. Whereas the Pecos River is incised, the depth of incision generally is not sufficient for the damming of the river to form impoundments. At a limited number of locations along the river, conditions were adequate for damming, and dams have already been constructed at these locations. The options for additional dams is severely limited. In addition, the Pecos River is approximately 24 kilometers (15 miles) from and more than 90 meters (300 feet) lower than the surface location of the waste panels. Because of the limited option of additional dams on the river and the distance of the river from the waste panels, damming of the Pecos River can be eliminated from consideration in performance assessments, because additional dams will be of no consequence to the disposal system.

Nash Draw is the most pronounced topographic feature in the vicinity of the WIPP (see Figure 7-35, U.S. DOE, 1980a). The draw is a collapse feature caused by the dissolution of underlying evaporites, and except for the southern boundary, the boundaries of the feature are relatively steep and of nearly uniform elevation. Nash Draw does not contain any perennial streams or rivers to dam. Creation of an impoundment within the draw will be considered with the possibility of water being supplied from outside of the feature. A dam across the southern end of the draw (approximately at the location of borehole WIPP-21) would have to be over 3 miles (5 kilometers) long, but such a dam would create a confined depression of approximately 40 square miles (103 square kilometers) and locally as much as 200 feet (61 meters) deep. One problem with creating this impoundment is how to confine the water. Collapse structures caused by the dissolution of evaporites beneath Nash Draw would provide pathways for water within the draw to reach underlying fracture zones, which would act as conduits for the water to leave the draw. The rocks and sediments at the margins of the feature also could drain impounded water. To create an impoundment in Nash Draw, large-scale leakage would have to be stopped or minimized or sufficient water supplied to the impoundment to make up for the losses. Another and perhaps fatal problem to creating an impoundment in this draw is providing enough water to fill the draw and maintain the water level. Filling the draw will be ignored in this discussion. In addition to leakage, evaporation would be a major source of water loss. Pan evaporation in valleys in southeastern New Mexico is approximately 110 inches (9.2 feet, 2.8 meters) per year (Powers et al., 1978b), which for a 40-square-mile impoundment in Nash Draw would result in the loss of approximately 235,000 acre-feet of water per year to evaporation alone. Evaporation would be approximately 12 times the annual flow of the Pecos River near Malaga (based on a time-weighted average of 26 ft^3/s; Powers et al., 1978b). Based on the mean annual precipitation at Carlsbad, which is 12 inches/year (30.5 centimeters/year) (Powers et al., 1978b), the evaporated quantity of water that would have to be replaced would be approximately 11 times the annual flow volume of the Pecos River. Major aquifer depletion would occur in the region if water wells were used to maintain the water level. In the future when regional demands for water are higher than today, the possibility of piping water from the Ogallala aquifer northeast of the WIPP or a major river in another part of the country (e.g., the Mississippi River) is not realistic. Because of the limited supplies of water in southeastern New Mexico and the high demands for water that an impoundment in Nash Draw would require, damming of Nash Draw is not retained for performance assessments because this event is not physically reasonable.

The reason for eliminating damming from performance assessments depends on the location of the topographic feature being considered for damming. For the Pecos River, additional dams and impoundments will have no consequence on the disposal system. Unless a sufficiently large source of water is located to replace the water lost to leakage, evaporation, and use for human activity, the construction of a dam to form an impoundment within Nash Draw seems to have a low probability of occurring.

4.1.5 EVALUATION OF REPOSITORY- AND WASTE-INDUCED EVENTS AND PROCESSES

This category of events and processes has the potential of occurring as a result of interactions of the engineered portion of the disposal system and the surrounding rock.

Caving and Subsidence

An excavation at depth is not inherently stable because of differential stresses exerted on inhomogeneous rock surrounding the opening. The collapse of rock fragments from units above a subsurface excavation into the opening is called caving. Depending on the size and depth of the excavation, caving may result in measurable subsidence of the overlying land surface within a relatively short time interval. For excavations in salt, salt creep will be a contributing factor in the filling of the opening. Caving and subsidence have the potential of affecting groundwater-flow patterns by enhancing the vertical hydraulic conductivity between water-producing units or providing a pathway for increased recharge or discharge.

For the waste-filled rooms and drifts at the WIPP, the amount of downward movement of the overlying rock is limited by the fact that the rooms and drifts will contain waste and backfill that can be compressed to certain limits. Gas generated by corrosion of metals, bacterial action, and/or radiolysis may be of sufficient pressure to impede the downward movement of rocks into the rooms and drifts. Whereas some caving of the roof can occur into an open excavation if the opening is not specifically designed for stability, any caving that does occur will be limited by the amount of space not occupied by the waste and backfill. Salt creep without fracturing will eventually become the dominant mode of deformation in the salt surrounding the rooms and drifts as the waste and backfill exert increasing resistance to the creeping salt.

If the excavation, waste emplacement, and backfilling of the rooms and drifts occur within a relatively short time interval, caving will be minor to nonexistent. The amount of subsidence that can occur depends on the difference between the initial and compressed porosities of the various waste types and backfill, the amount of upward creep of the floor, the inward creep of the walls, the downward creep of the ceiling, and the gas pressure within the rooms and drifts.

Because of uncertainty about gas generated within the rooms and drifts, specific data do not exist with which to determine the amount of salt creep that will occur into the rooms and drifts after closure, and the amount of subsidence at the surface that will accompany this creep. Subsidence at potash mines in the northern Delaware Basin may serve as an analog for the process in the absence of pressurized gas. Mines in this region typically operate at final extraction ratios ranging from 40 to 60 percent. With 6-foot (1.8-meter) openings in production areas and no backfill, the maximum predicted subsidence at the surface is approximately 2 feet (0.7 meters) (Brausch et al., 1982). Based on data from Rechard et al. (1990a), the extraction ratio for the planned waste panels will be 0.22. This much lower extraction ratio along with the presence of both waste and backfill within the rooms and drifts suggests that surface subsidence over the WIPP should be less, and perhaps substantially less, than the maximum predicted subsidence of 2 feet (0.7 meters) over potash mines in the area.

Predicting the specific amount of subsidence that may occur over the waste panels requires a subsidence model. Because no TRU waste-disposal facilities exist, no validated subsidence models exist for these types of facilities. An alternative approach is to adopt subsidence models developed for other types of subsurface openings, such as coal mines. The use of models for analogous openings also does not solve the problem. According to Lee and Abel (1983) with regard to subsidence over coal mines,

> The difference in rock-mass behavior caused by site conditions alone would indicate that subsidence prediction and engineering cannot be treated in purely mathematical terms. Although the NCB [British National Coal Board] has developed quantitative, practical assessments of mining effects in the United Kingdom, there is no generally applicable subsidence model for the United States, nor are there adequately tested, empirical models for any of the major U.S. coal fields... (Lee and Abel, 1983, p. 25).

In an attempt to determine rough estimates of realistic bounds on the amount of subsidence that may occur over the waste panels, some simplified calculations have been performed. As a first step, the horizontal cross-sectional area of the waste panels is converted from a rectangle to a circle to simplify the subsequent calculations. The dimensions of the waste panels are 2064 feet (629 meters) by 2545 feet (776 meters) (WEC, 1989), and a circle with an equivalent area has a radius of 1293 feet (394 meters).

The next step is to determine the area at the surface above the waste panels that will subside. Subsidence will occur over an area larger than the subsurface excavations, but at some distance laterally from the excavations, no subsidence will occur. The angle between a vertical line from the edge of the excavation to the surface and a line from the same edge of the excavation to the boundary between subsidence and nonsubsidence on the surface is called the angle of draw (α), which is also called the limit angle (Figure 4-3). A major problem is that data are insufficient in the northern Delaware Basin with which to derive or approximate a value of α for the WIPP.

Lee and Abel (1983) report that data collected by the NCB for longwall (as opposed to room and pillar) coal mines in Britain have a range of α from 25° to 35° with the range being much wider (but unspecified) when worldwide measurements are included. Although the WIPP waste panels are more analogous to room and pillar mines rather than longwall mines, no data are readily available for room and pillar mines, so the upper and lower values of the

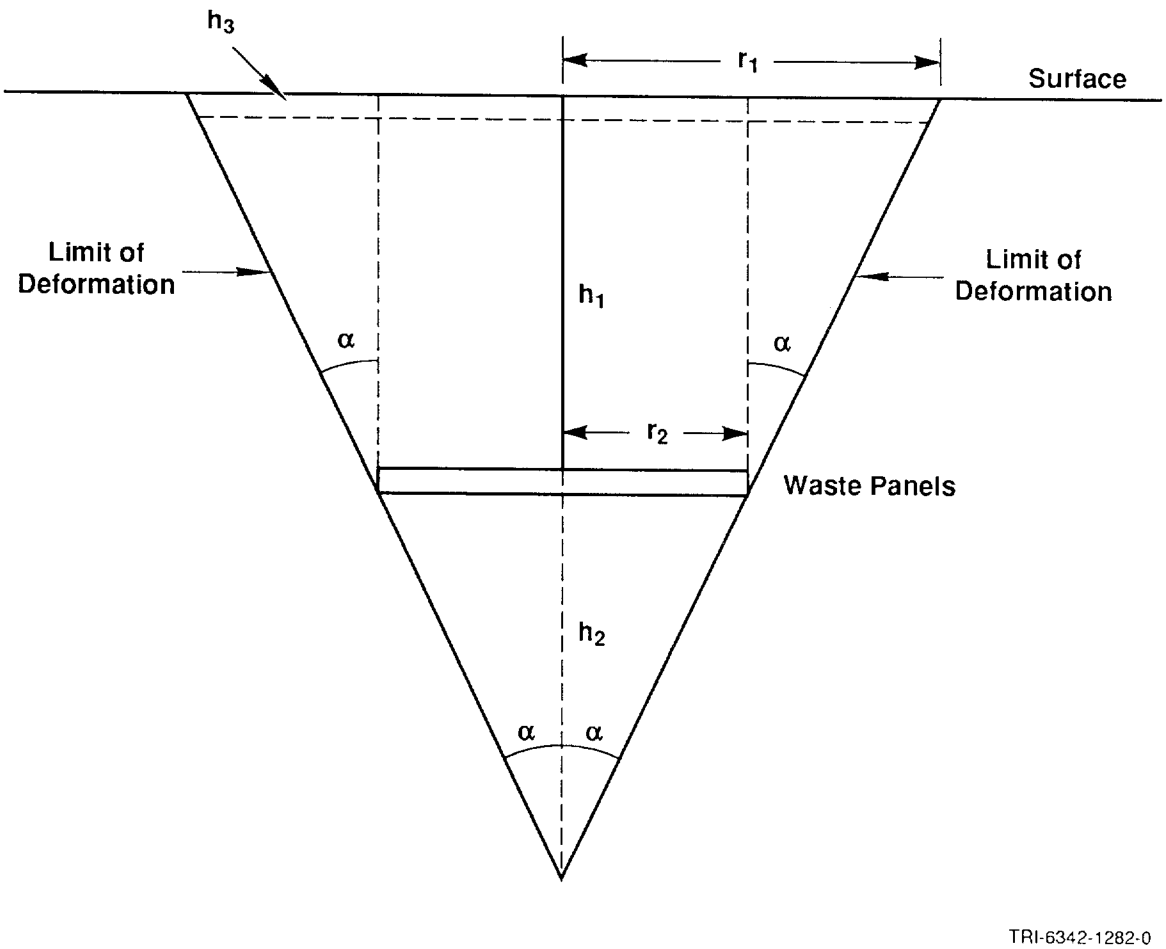


Figure 4-3. Cross-Sectional Areas of Subsidence Over Waste Panels.

range of values reported by the NCB will be used to roughly determine the area of surface subsidence.

In Figure 4-3, the radius of the subsidence area is r_1. The length of r_1 can be determined from the relationships

$$\tan \alpha = \frac{r_1}{(h_1 + h_2)} \tag{4-2}$$

and as a result,

$$r_1 = \tan \alpha \times (h_1 + h_2) \tag{4-3}$$

where h_1 is the depth of the waste panels beneath the surface (2150 feet) (655 meters) and h_2 is the depth from the panels to the point where the downward projection of the lateral limits of the zone of subsidence would converge at depth. Although the value of h_2 is not known directly, this distance can be calculated from the relationship

$$\tan \alpha = \frac{r_2}{h_2} \tag{4-4}$$

which becomes

$$h_2 = \frac{r_2}{\tan \alpha} \tag{4-5}$$

where r_2 is the radius of the circular representation of the area of the waste panels. The value of r_2 is 1293 feet (394 meters).

For a value of α equal to 25°, h_2 in Equation 4-5 equals 2774 feet (845 meters). Substituting the appropriate values into Equation 4-3,

$$r_1 = \tan 25° \times (2150 \text{ feet} + 2774 \text{ feet}) = 2296 \text{ feet (700 meters)}.$$

For a value of α equal to 35°, h_2 in Equation 4-5 equals 1847 feet (394 meters). Substituting the appropriate values into Equation 4-3,

$$r_1 = \tan 35° \times (2150 \text{ feet} + 1847 \text{ feet}) = 2799 \text{ feet (853 meters)}.$$

The next step is to determine the volume change in the waste-filled rooms and drifts that must be accommodated by subsidence. Several assumptions must be made at this point in this procedure. One assumption is that gas generated by corrosion, microbial activity, or radiolysis does not affect the compression of the waste and backfill by salt creep. Another assumption is that all of the volume change in the rooms and drifts will be expressed as subsidence at the surface. This second assumption requires that the rock units between the waste panels and the surface have no competence. Rock units that do have competence may bend without suffering complete failure when the support of underlying units is lost, thereby causing gaps (bed separations) to form between adjacent units. The formation of these gaps distribute some of the subsidence within the subsiding volume of material rather than entirely at the surface.

Salt creep will compress the contents of the waste-filled rooms and drifts until the differential stresses have equalized. The rooms and drifts will contain a variety of waste types with the addition of backfill, which is assumed to consist of 70 percent crushed salt and 30 percent bentonite. Calculations by Butcher (1991) indicate that an average void fraction of an entire room of approximately 63 percent will be reduced to approximately 16 percent over a period of several hundred years. Rechard et al. (1990a) reported the expected volume of excavated disposal rooms and drifts at the WIPP to be 433.3×10^3 m^3 (1.53×10^7 ft^3). When the rooms and drifts are fully loaded with waste and backfill, 63 percent of the original excavated volume will remain as pore space, which will be equal to 2.72×10^5 m^3 (9.60×10^6 ft^3). Upon compaction by salt creep to a porosity of 16 percent, the rooms and drifts will contain approximately 6.93×10^4 m^3 (2.45×10^6 ft^3) of void space. The change in volume will be 2.04×10^5 m^3 (7.20×10^6 ft^3). This change in volume is assumed to be the volume of surface subsidence that will occur over the waste panels.

To accommodate the volume of subsidence, the area of subsidence is assumed to subside uniformly, thereby forming a cylinder with the amount of surface subsidence represented by the height of the cylinder. The volume of a cylinder is

$$V = \pi r^2 h_3 \tag{4-6}$$

where h_3 is the amount of surface subsidence, and r is the r_1 in Equations 4-2 and 4-3 and Figure 4-3. From Equation 4-6,

$$h_3 = \frac{V}{\pi r^2} \,. \tag{4-7}$$

For α equal to 25°, r_1 is equal to 2296 feet (700 meters). To accommodate a volume of subsidence V equal to 7.20×10^6 ft^3 (2.04×10^5 m^3) in Equation 4-7, h_3 equals 0.43 feet (0.13 meters). For α equal to 35°, r_1 equals 2799 feet (853 meters), and h_3 then equals 0.29 feet (0.088 meters).

Although the actual value of α for the WIPP geologic setting (including the effects of lateral salt-creep closure of the rooms and drifts), extraction ratio, and waste and backfill conditions is not known, the above calculations indicate the approximate magnitude of subsidence that may occur over the waste panels. The next step in screening this process is to determine whether subsidence on this order of magnitude has an effect on the disposal system.

No direct information or data are available on the effects of subsidence on the overlying groundwater-flow system in the northern Delaware Basin. An alternative approach is to examine whether shallow dissolution in the WIPP has affected groundwater flow. Removal of salt by dissolution leaving the insoluble constituents reportedly is the origin for the Rustler-Salado contact residuum (Robinson and Lang, 1938; Mercer and Orr, 1977; Mercer, 1983). If the subsequent lowering of the overlying units in response to the removal of the salt has not disrupted the groundwater-flow system in these overlying units, perhaps the subsidence over the waste panels also will not affect the flow system.

Data compiled in Brinster (1991) indicate that the thickness of the contact residuum within the boundary of the WIPP ranges from 7 to 16 meters (23 to 52 feet) with a seemingly anomalous thickness in borehole H-16 of 36 meters (118 feet). A substantially thicker sequence of salt had to be removed to leave these thicknesses of insoluble residue. Based on data for nine sampled intervals of salt from borehole ERDA-9 (Powers et al., 1978b), the weighted average of the percent insoluble residue in salt is 4 percent at this location. This value was assumed to be representative of the amount of insoluble residue in salt for the Salado Formation within the boundaries of the WIPP. If a 7-meter (23-foot) thickness of insoluble residue represents 4 percent of the predissolution thickness of salt, the salt would have been 175 meters (574 feet) thick prior to dissolution. A 16-meter (52-foot) thickness of residue corresponds to 400 meters (1312 feet) of salt prior to dissolution.

The presence of the Rustler-Salado contact residuum suggests that a substantial thickness of salt has been dissolved in order to leave the thicknesses of insoluble residue that have been recorded in boreholes at the WIPP. Both the Culebra and Magenta Dolomite Members of the Rustler Formation continue to be confined water-producing units. If the units overlying the contact residuum have been lowered hundreds of meters without disrupting confined hydrologic units in the Rustler Formation, the fraction of a meter of additional lowering of units overlying the waste panels should not be expected to disrupt the confinement of the water-producing units between the waste panels and the surface.

Caving and subsidence associated with the presence of the waste panels will not be included in performance assessments of the WIPP because of the lack of consequences of these phenomena.

Shaft and Borehole Seal Degradation

The engineered facility for the WIPP includes four shafts from the surface to the level of the waste panels. At decommissioning of the facility, these shafts will be sealed in order to prevent water above the Salado Formation from reaching the waste, and to prevent water that may accumulate in the rooms and drifts from having a pathway to overlying units or to the surface. Two types of seals are planned for the shafts. One type is designed to be temporary, consisting of concrete and bentonite-based materials to prevent the downward flow of water long enough for the second type of seal to consolidate. The other type is long term and will consist of crushed salt possibly with a component of swelling clay (Nowak et al., 1990). Closure of the shafts by salt creep is expected to consolidate the seal material to a point where the hydrologic properties of the seals are approximately the same as intact salt.

Degradation of the shaft seals is of concern to performance assessments because of the possibility that the shafts could provide a pathway for groundwater flow to or from the waste-filled rooms and drifts. Because the concrete seals are designed to be temporary, their degradation is not relevant to the long-term performance of the disposal system. The lower seals are not expected to degrade, although the final properties of the seal material are not known. A degraded seal or a seal that has not fully consolidated is likely to have similar properties that can be incorporated into modeling as parameter variability. The condition of the shaft seal must be considered in every scenario analyzed in a performance assessment. For this reason, possible degradation of shaft seals is part of the base-case scenario. No mechanism for the WIPP setting has been recognized as a possible cause of massive, instantaneous failure of shaft seals.

If boreholes for resource exploration are drilled into the waste panels, these boreholes have the potential of providing pathways for groundwater flow. Whereas considerable care will be used for the proper emplacement of shaft seals at decommissioning, neither composition nor care of emplacement can be assured for borehole seals. As with shaft seals, the hydrologic properties of a degraded seal are likely to be similar to the properties of an improperly emplaced seal. The condition of the borehole seals must be considered in each scenario that contains an exploratory-drilling event. Because the properties of the seals can range from intact to totally degraded, these properties can be incorporated into the modeling of system performance as uncertainty in input variables. No mechanism for the WIPP setting has been recognized as a possible cause of massive, instantaneous failure of borehole seals. Appendix B of the Standard provides guidance as to the "worst-case" properties of borehole seals that need to be considered in performance assessments, although alternate properties can be used.

Thermally Induced Stress Fracturing in Host Rock

If the thermal load of the radioactive waste placed in a disposal facility is sufficiently high, the potential exists for fractures to form in the host rock in response to expansion and contraction of the rock, thermal contrasts in the rock, or a large amount of thermal expansion of confined rock. These fractures could provide pathways for groundwater flow with much higher permeabilities than the intact host rock.

Because the waste destined for the WIPP will be low level, no thermal effects within the waste or on the surrounding rock are expected. Preliminary analysis (Thorne and Rudeen, 1979) assumed that drums and boxes loaded in the WIPP contain the maximum permissible plutonium content, which would result in a thermal load 25 times higher than expected for contact-handled waste (U.S. DOE, 1980a). The maximum rise in temperature at the center of the repository was calculated to be less than 2°C at 80 years after waste emplacement with the temperature quickly dropping to less than 1°C above ambient for the remainder of the analysis. Temperature increases of the magnitude determined in the analysis by Thorne and Rudeen (1979) will not result in the fracturing of the salt host rock for the WIPP.

Thermally induced fracturing of the Salado Formation can be eliminated from consideration in the WIPP performance assessments based on the physical unreasonableness of fracturing of this origin.

Excavation-Induced Stress Fracturing in Host Rock

Excavations alter the stress field in the rock surrounding the opening and provide an area into which rocks that had been under compression can expand. This expansion of the rock creates a disturbed zone of both microfractures and macrofractures within the rock that alters the mechanical and hydrologic properties around the opening. As with thermally induced fractures, excavation-induced fractures could provide pathways for groundwater flow around engineered barriers or act as sinks for the accumulation of fluids.

At the excavations for the WIPP, boreholes drilled for stratigraphic studies, experiments, and construction have encountered a zone of fractures surrounding the rooms and drifts, and the altered properties of the rock have been confirmed by geophysical surveys and gas-flow tests (Lappin et al., 1989). This zone is referred to as the disturbed-rock zone (DRZ). The DRZ ranges from 1 to 5 feet (0.3 to 1.5 meters) in width depending on the size and age of a particular opening (Lappin et al., 1989). Drifts with relatively narrow widths do not have associated DRZs at present (U.S. DOE, 1988), although with sufficient time, a DRZ is likely to form around all of the rooms and drifts. After closure of the facility, salt creep will tend to close the DRZ once sufficient backpressure is exerted by the waste and backfill against the salt. Whether the properties of the DRZ will return to those of intact salt has not been determined.

The presence or absence of a DRZ around the waste-disposal rooms and drifts must be included in all scenarios analyzed for performance assessment. Because the DRZ is part of each scenario, this feature is part of the conceptual model for the base-case scenario.

Gas Generation

After the rooms and drifts at the WIPP are filled and sealed, various gases may be formed by the corrosion of metals in the waste and containers, microbial decomposition of organic material in the waste, reactions between the corrosion products of the metals and the microbially generated gases, and reactions between backfill constituents and gases and water (Brush and Anderson, 1988a). An additional gas-generating process is radiolysis. The generation of gas is of interest to performance assessment because sufficiently high gas pressures have the potential of re-expanding the waste-filled rooms and drifts, developing a new or maintaining an existing DRZ, and creating fractures in Marker Bed 139 and/or other marker beds along which waste could migrate (Lappin et al., 1989). Other possible effects include the limitation on the amount of brine that flows into the rooms and drifts, and the possible expulsion of degraded waste into a borehole during human intrusion.

WIPP waste is certain to contain some water as free liquid and moisture absorbed in the waste. Additional liquid water and vapor are likely to be introduced by the influx of brine from the Salado Formation. Anoxic corrosion of the waste drums and metallic waste is expected to be the dominant producer of gas, although microbial breakdown of cellulosic material and possibly plastics and other synthetic materials also is likely to occur (Lappin et al., 1989). For waste representative of the expected CH-TRU waste in rooms and drifts, radiolysis is not expected to contribute significant amounts of gas to the total amount produced (Slezak and Lappin, 1990). The amount of water available for reactions and microbial activity will have a major impact on the amounts and types of gases produced.

The generation of gases within the rooms and drifts is certain to occur. For this reason, any effects of gas generation on the disposal system must be included in each of the scenarios analyzed in performance assessment. Because gas generation is part of each scenario, this process is an integral part of the conceptual model for the base-case scenario.

Explosions

Corrosion of metals in the waste and waste containers along with microbial breakdown of various waste constituents will produce gases that have the potential to be flammable or explosive. Explosions in the waste-filled rooms and drifts after decommissioning are of concern to performance assessments because of possible damage to engineered barriers that could generate pathways for groundwater flow.

Gases generated by corrosion and microbial activity would tend to collect in the upper portions of the rooms and drifts. To address the question of possible damage to panel seals, Slezak and Lappin (1990) assumed the "worst-case" (most potentially detonable) mixture of methane, hydrogen, and oxygen in the 1.5-foot (0.5-meter) head space of the rooms and drifts approximately five years after panel-seal emplacement. Based on several assumptions to optimize the effects of an explosion, the peak pressure pulse reaching the panel seal was calculated to be 800 psi, which would have no consequences on the performance of the panel seal. The pressure would decay to 120 psi at 0.35 seconds after impact.

Waste-induced explosions can be eliminated from consideration in the WIPP performance assessments based on the lack of consequences of such events.

Nuclear Criticality

Nuclear criticality refers to a sufficiently high concentration of radionuclides for a sustained fission reaction to occur. This type of reaction produces heat, or under a specific set of conditions, causes an explosion. Nuclear criticality is important to performance assessment because a heat source could form thermal convection cells in the groundwater, fracture brittle rocks as a result of differential thermal expansion, or possibly cause a steam explosion. A nuclear explosion would be important because such an event could result in total failure of the disposal system and directly release radionuclides to the accessible environment.

In the nuclear-waste disposal environment, the radionuclides that could result in nuclear criticality are present, although a concentration process is required to create a critical mass. The waste acceptance criteria (draft of WIPP-DOE-069-Rev. 4, as explained in Chapter 1 of this volume) for nuclear waste destined for the WIPP sets limits on the amount of fissile radionuclide content of CH- and RH-waste containers. Operations and safety criteria limit the Pu-239 fissile gram equivalents (FGE) to less than 200 grams (0.4 pounds) in 55-gallon (0.21 m^3) drums, 100 grams (0.2 pounds) in 100-gallon (0.38 m^3) drums, 500 grams (1.1 pounds) in DOT M6 containers, and 5 grams (0.01 pounds) per ft^3 (0.028 m^3) in other waste boxes (up to a 350 gram (0.77 pounds) maximum) for CH waste. RH-waste containers are limited to no more than 600 grams (1.3 pounds) in Pu-239 FGE. Transportation standards for the waste generally are more strict in the FGE content of containers than the operations and safety criteria. The Pu-239 FGE must be less than 200 grams (0.4 pounds) for CH drums, 325 grams (0.7 pounds) for standard waste boxes, and 325 grams (0.7 pounds) for a TRUPACT-II container. RH-waste containers may be limited to less than 325 grams (0.7 pounds) per cask.

Calculations performed to support the WIPP *Final Environmental Impact Statement* (U.S. DOE, 1980a) indicated that a CH-waste drum holding 140 kilograms (308 pounds) of waste would have to contain more than 5 kilograms (11 pounds) of plutonium to potentially form a critical mass. As stated in the report, most drums will contain less than 0.01 kilograms (0.02 pounds) of plutonium, with the maximum allowed plutonium content of 0.2 kilograms (0.4 pounds) per drum. Although RH waste was not included in the calculations, the maximum allowable FGE content of RH waste per container allowed by the operations and safety criteria is far below the minimum calculated amount of plutonium required to form a critical mass under optimum dry conditions.

Because of the relatively low plutonium content of the waste containers, nuclear criticality within dry CH- and RH-waste containers has a probability of occurrence of 0. Water within the containers introduces an altered set of conditions whose effects on criticality have not been evaluated at this time. The possibility also exists that some of the plutonium will be dissolved by groundwater and transported along any of various pathways through all or part of the disposal system. Depending on the geochemical environment along any particular transport path, the plutonium could precipitate or sorb in the backfill, at certain components of the seal system, or within the Culebra Dolomite Member or other hydrologic units. The WIPP performance-assessment team has not determined at this time whether concentration of plutonium can reach critical mass at any of these locations.

For a high-yield nuclear explosion to occur within the waste containers, a critical mass of plutonium would have to undergo rapid compression to a high density (U.S. DOE, 1980a). The lack of a critical mass within the waste containers requires that the probability of a nuclear explosion occurring within the waste be assigned a value of 0, even without considering the improbability of the other required conditions. In soils, Stratton (1983) concluded that for a critical mass of plutonium to result in a high-yield explosion would require either a large amount of plutonium to be concentrated in an appropriate geometry or an unrealistically large amount of water to be present to act as a reflectant. While not considering the WIPP disposal system directly, Stratton's analysis of the conditions required in soils for a nuclear explosion to occur indicate that explosions of this origin can be eliminated from the WIPP performance assessment on the basis of low probability.

Nuclear criticality as a possible source of heat within the disposal system is retained for additional evaluation before a screening decision is made.

4.1.6 SUMMARY OF SCREENED EVENTS AND PROCESSES

None of the natural events and processes listed in Table 4-1 is retained for scenario development (Table 4-2). Phenomena such as erosion, sedimentation, and climatic change (pluvial periods) are certain to occur during the next 10,000 years, which indicates that these phenomena are part of the conceptual model for the base-case scenario. The effects of other events (i.e., sea-level variations, hurricanes, seiches, and tsunamis) are restricted to coastal areas. Because of the geologic stability of the WIPP region, changes in the tectonic setting that would result in the occurrence or recurrence of the subsurface events and processes (except for seismic activity) are not physically reasonable in the time frame of regulatory concern. Seismic activity has the potential of affecting the source term, and these effects can be addressed in the source-term uncertainty during modeling. Regional subsidence or uplift, mass wasting, and flooding are not likely to occur to an extent that would affect the performance of the disposal system.

Of the human-induced events and processes, explosions can be eliminated from consideration because of low probability and low consequence for inadvertent explosions during warfare and nuclear testing, respectively. Irrigation and damming of valleys are not physically reasonable without major technological innovations in response to poor water quality and limited water supplies. Exploratory drilling for resources and drilling injection wells are both realistic events for the WIPP, although injection wells are expected to be of no consequence to the performance of the disposal system. Based on the geologic setting and previous resource evaluations, exploratory drilling for resources is retained for scenario development, while injection wells are excluded based on regulatory guidance and low consequence. Exploratory drilling is subdivided into two possibilities: drilling into a waste-filled room or drift and a brine reservoir in the underlying Castile Formation (Event E1), and drilling into a waste-filled room or drift but no brine reservoir (Event E2). Mining (Event TS) is limited to potash extraction by either conventional or solution methods in areas beyond the boundaries of the waste panels, and drilling of withdrawal wells (Event E3) is limited to water wells in areas where water quantity and quality will permit water use. Both

TABLE 4-2. SUMMARY OF SCREENED EVENTS AND PROCESSES

	RETAINED		SCREENED OUT			
Events and Processes	Undisturbed Conditions	For Scenario Development	Low Probability	Physically Unreasonable	Low Consequence	Regulator Requirements
Natural						
Meteorite Impact			X			
Erosion/Sedimentation	X					
Glaciation				X		
Pluvial Periods (Climate Change)	X					
Sea-Level Variations				X		
Hurricanes				X		
Seiches				X		
Tsunamis						
"Conventional"				X		
Metorite Impact			X			
Regional Subsidence or Uplift				X		
Mass Wasting				X		
Flooding				X		
Diapirism				X		
Seismic Activity	X					
Volcanic Activity				X		
Magmatic Activity				X		
Formation of Dissolution Cavities						
Deep Dissolution				X		
Shallow Dissolution						
Rustler-Salado Contact	X					
Nash Draw*			X	X		
Formation of Interconnected						
Fracture Systems				X		
Faulting				X		

*Screening criterion depends on which possible mechanisms considered for origin of Nash Draw.

TABLE 4-2. SUMMARY OF SCREENED EVENTS AND PROCESSES (continued)

Events and Processes	RETAINED		SCREENED OUT			
	Undisturbed Conditions	For Scenario Development	Low Probability	Physically Unreasonable	Low Consequence	Regulator Requirements
Human-Induced Explosions						
At Waste-Panels Location						X
Near Waste-Panels Location						
At Surface/Warfare			X			
Deep Testing			X			
Drilling (Exploratory)		X				
Mining						
At Waste-Panels Location						X
Near Waste-Panels Location		X				
Injection Wells					X	
Withdrawal Wells						
Water Wells		X				
Oil and Gas Wells						
At Waste-Panels Location						X
Near Waste-Panels Location					X	
Irrigation			X			
Damming of Streams and Rivers						
At Pecos River					X	
Near Nash Draw			X			
Repository- and Waste-Induced						
Subsidence and Caving					X	
Shaft & Borehole Seal		X				
Degradation	X					
Thermally Induced Fractures				X		

TABLE 4-2. SUMMARY OF SCREENED EVENTS AND PROCESSES (concluded)

	RETAINED		SCREENED OUT			
Events and Processes	Undisturbed Conditions	For Scenario Development	Low Probability	Physically Unreasonable	Low Consequence	Regulator Requirements
Excavation-Induced Fractures	X					
Gas Generation	X					
Explosions (Gas Ignition)					X	
Nuclear Criticality						
Critical Mass (Explosion)			X			
Sustained Reaction**						

**Retained for additional evaluation.

the mining and water wells are being evaluated for their effects on groundwater flow in the WIPP area.

In the category of waste- and repository-induced events and processes, gas generation and shaft-seal degradation are part of the conceptual model of the base-case scenario. Borehole seal degradation can be addressed through parameter uncertainty during modeling. Excavation-induced fracturing in the host rock can be handled by including the disturbed zone surrounding mined openings in the conceptual model of the base-case scenario. Caving into the rooms or drifts may occur in the short term after closure, but this process has no long-term consequences on performance because of the mechanical behavior of salt. Thermally induced fracturing of the host rock is not a physically reasonable phenomenon because of the low thermal output of WIPP waste. Subsidence caused by the mined openings and explosions caused by the ignition of gases created by waste degradation have no effect on the performance of the disposal system and can be eliminated from scenario development. Nuclear criticality requires additional evaluation before a screening decision is made.

4.1.7 DEVELOPING SUMMARY SCENARIOS

To construct a CCDF, the summary scenarios used in the performance assessment should be comprehensive and mutually exclusive subsets of the sample space *S*. 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).

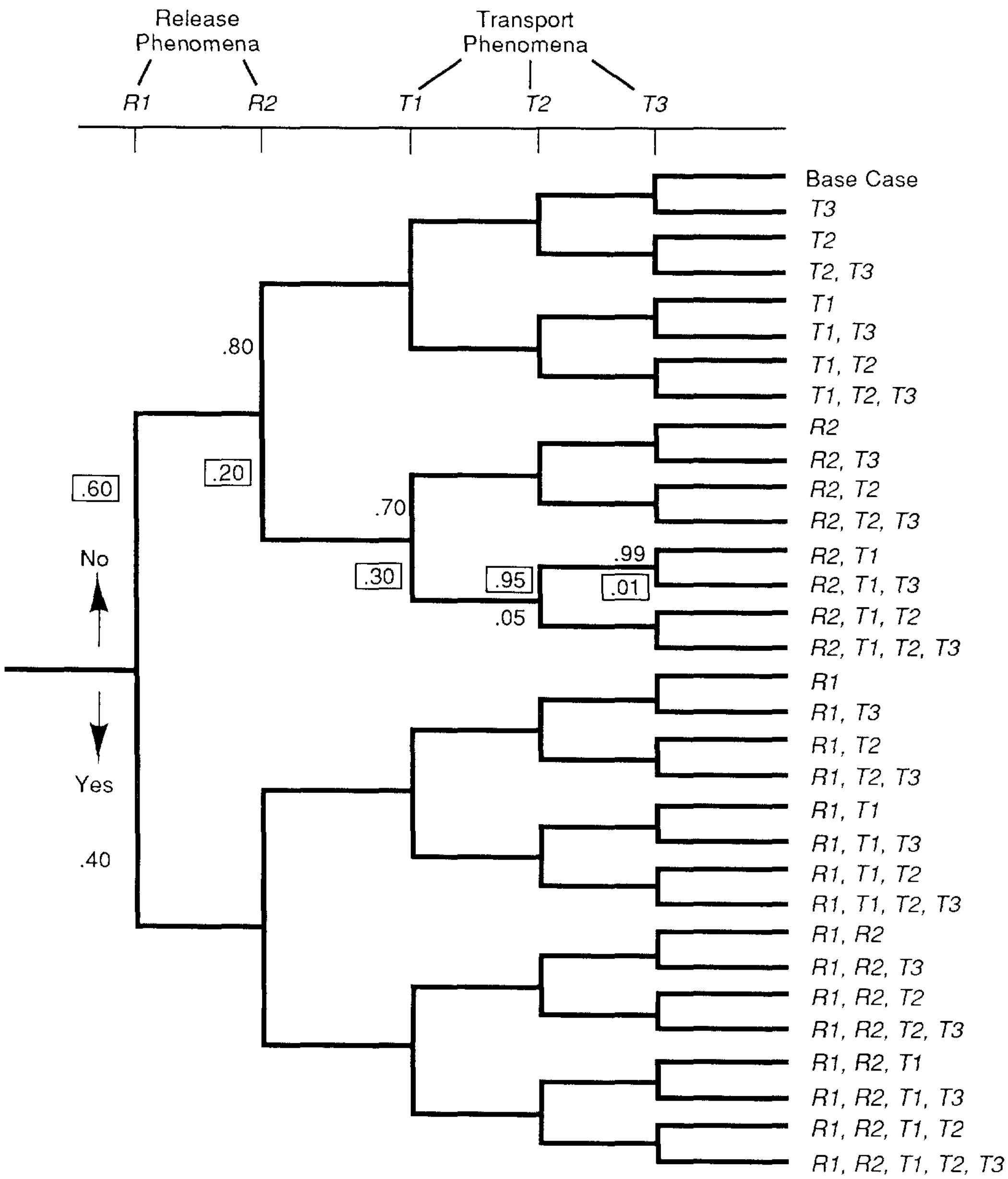
Event trees for scenario development have not been able to produce reasonable numbers of well-defined and mutually exclusive scenarios that can be analyzed probabilistically to address the current formulation of the Standard (Guzowski, 1990). An alternative approach addresses these problems through logic diagrams (Figure 4-4) (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. 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 (i.e., define the sample space S), 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.

Figure 4-5 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.

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.

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 4-4). The probability of a scenario is the product of the probabilities along the pathway through the logic diagram that defines that scenario (see Figure 4-4



☐ 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}

Notes: (1) Expressions of the form *R2, T1, T3* are an abbreviation for $R1^c \cap R2 \cap T1 \cap T2^c \cap T3$ (i.e., intersections and complements are omitted from the notation).

(2) Indicated probability calculation assumes that *R1, R2, T1, T2, T3* are independent events. That is, $p(R1 \cap R2 \cap T1 \cap T2 \cap T3) = p(R1)\,p(R2)\,p(T1)\,p(T2)\,p(T3)$.

(3) If the events *R1, R2, T1, T2, T3* are not independent, then the ordering in the tree is important because conditional probabilities must be used.

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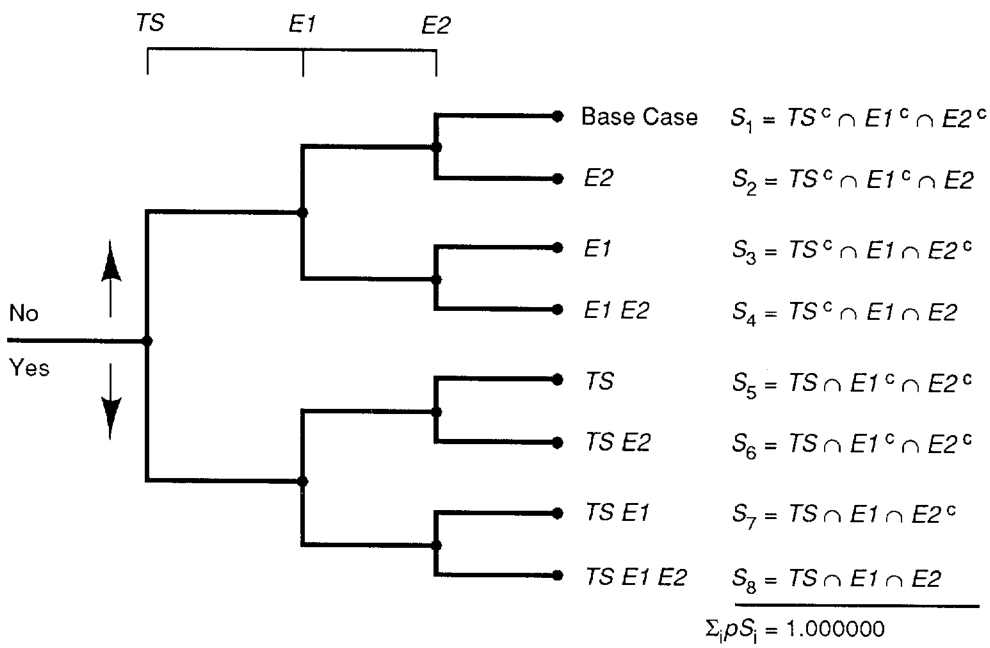
Figure 4-4. **Example of a Logic Diagram with Two Events Affecting Release (R) from a Repository and Three Events Affecting Transport (T) to the Accessible Environment for the Construction of Scenarios (after Cranwell et al., 1990), Illustrating Scenario Probability Assignment.**



x = 10,000 yr Time History

TS = {x: Subsidence Resulting From Solution Mining of Potash}

E1 = {x: One or More Boreholes Pass Through a Waste Panel and into a Brine Pocket}

E2 = {x: One or More Boreholes Pass Through a Waste Panel Without Penetration of Brine Pocket}

Superscript c (e.g., TS^c) Denotes Set Complement

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Figure 4-5. Potential Scenarios for the WIPP Disposal System.

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 1 chance in 10,000 in 10,000 years need not be considered in determining compliance with 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 remaining probability distribution of cumulative releases. 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 data base, 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 of Retained Scenarios

This section describes the scenarios retained for consequence analysis.

Undisturbed Performance Summary Scenario (Base Case, S_B)

The Individual Protection Requirements of the Standard (§ 191.15) call for a reasonable expectation that the disposal system will 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)), "'[u]ndisturbed 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." 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; Bertram-Howery et al., 1990).

Base-Case Summary 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 4-4). 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 migration of hazardous (RCRA) wastes 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 (Nowak et al., 1990).

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 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 (Bertram-Howery et al., 1990).

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.

Two pathways for groundwater flow and radionuclide transport dominate the disposal system (Figure 4-6). In the first path, brine and 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. Following repository decommissioning, waste-generated gas will begin to pressurize the waste panels (Weatherby et al., 1989). Brine will drain by gravity to the lower half of the panels. Gas will saturate the DRZ above the panel and open flow paths to anhydrite layers A and B above the panel. MB139 beneath the panel will remain brine saturated, but gas will open flow paths into the MB139 beyond the panels. The more-mobile gas phase will flow outward over the less-mobile brine phase. After gas generation ceases, pressure and phase distribution will gradually equilibrate throughout the entire region. Gas will continue to expand outward, but brine flow reverses, flowing inward primarily along the lower portions of anhydrite layers A and B and MB139. Gas saturation near the waste panels will diminish. The anhydrite layers above the waste panels will be a major flow path for gas. In contrast, brine will inhibit gas inflow in the MB139 beneath the waste panels.

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 resulting from waste-

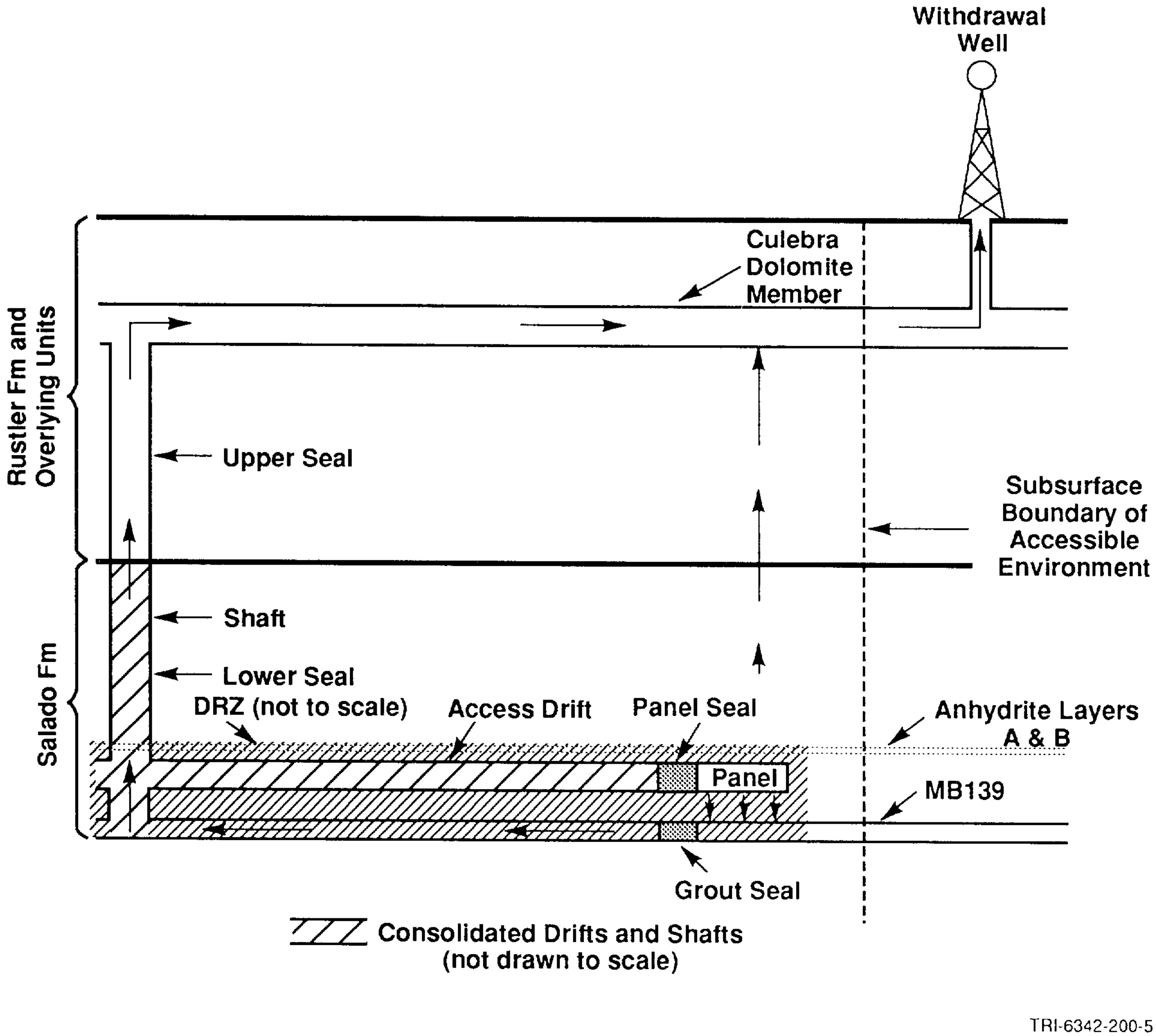

Figure 4-6. Conceptual Model Used in Simulating Undisturbed Performance.

generated gas (approximately 15 MPa+) and hydrostatic pressure at the Culebra (1 MPa) tends to force radionuclide-bearing brine from MB139 beneath the panel through the seal in the marker bed, along the fractures in MB139 to the base of the shaft. Concurrently, gas flows through the upper portion of the drifts and the anhydrite layers A and B to the shaft. Gas saturation in the shaft seals will inhibit brine migration up the shaft to the Culebra Dolomite Member. Brine and radionuclides will eventually reach the Culebra and migrate downgradient to the accessible environment.

Relative motion during salt creep and gas generation prevents 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 is considered for other analyses (see Volume 2 of this report).

The other dominant path is assumed to be from the repository vertically through the intact Salado Formation toward the Culebra Dolomite Member (Figure 4-6) (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.

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. Waste-generated gas pressurizes the waste panels, forcing radionuclide-bearing brine to 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 humans, 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 are released into the Culebra in 1,000 years, this route is not completed, and no need exists to consider other possible pathways for § 191.15 at this time, although this position may change when the Standard is repromulgated.

Human-Intrusion Summary Scenarios

Appendix B of the Standard (U.S. EPA, 1985) provides guidance on a number of factors concerning human intrusion. The section "Institutional Controls" in Appendix B (U.S. EPA, 1985, p. 38088) 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 "Consideration of Inadvertent Human Intrusion into Geologic Repositories" in Appendix B (U.S. EPA, 1985, p. 38088) suggests that exploratory drilling for resources can be the most severe form of human intrusion considered. The section "Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories" in Appendix B (U.S. EPA, 1985, p. 38089) 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.

Intrusion Borehole into a Room or Drift (Summary Scenario *E2*)

Scenario *E2* consists of one or more boreholes that penetrate to or through a waste-filled room or drift in a panel (Figure 4-7). 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 is propped open by the sand-like material.

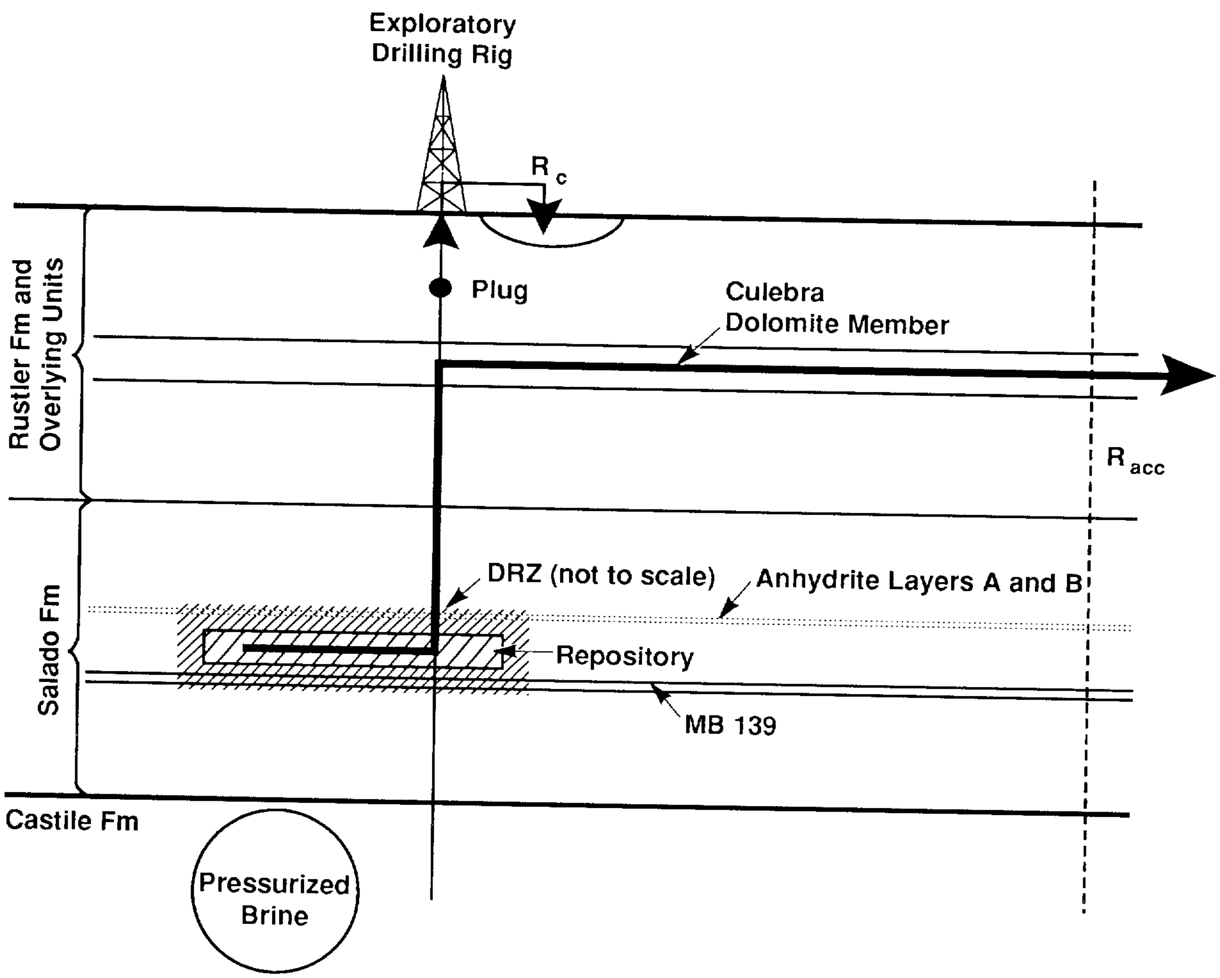

Figure 4-7. Conceptual Model for Scenario *E2*. Arrows indicate assumed direction of flow. Exploratory borehole does not penetrate pressurized brine below the repository horizon. R_C is the release of cuttings and eroded material. R_{acc} is the release at the subsurface boundary of the accessible environment. A plug above the Culebra Dolomite Member is assumed to remain intact for 10,000 years.

After the repository is decommissioned, moisture in the waste or brine from the host rock allows microbiological activity and corrosion to occur, generating gas. Repository conditions would evolve according to the previous description of the undisturbed scenario. At the time of intrusion into a waste panel, gas could vent through the intruding borehole, thereby allowing the repository to resaturate. The rapid venting of waste-generated gas may result in spalling of waste material into the borehole and eventual removal to the surface by drilling fluid. 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.

After drilling is completed, the hole is plugged. Because hydraulic head in the Culebra Dolomite Member is less than hydraulic head of the repository, the connection between the repository and the Culebra Dolomite provides a potential pathway for flow of water and gas from the repository to the Culebra. This process forces water and gas from the repository and nearby members (Figure 4-7) into the borehole and upward to the Culebra Dolomite Member. Brine, puddled beneath the waste in MB139, inhibits gas flow through this member towards the borehole. However, gas in the upper portion of the waste panel and overlying anhydrite layers A and B will migrate into the borehole fill, saturating the borehole. Brine flow from the lower member will be inhibited by this gas cap in the borehole. Brine flowing from the intact halite and anhydrite will eventually displace the gas. When brine saturation in the waste panel exceeds residual brine saturation (approximately 20 percent), flow through the waste will resume. When brine saturations exceed about 60 percent, significant flow into the borehole will occur. The time delay between intrusion and significant brine and radionuclide release to the Culebra Dolomite Member may be significant and will depend on a number of material property values and coupled processes discussed in Chapter 5 of this volume and Volume 2, Chapter 4 of this report. 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 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 (Summary Scenario *E1*)

Scenario *E1* (Figure 4-8) consists of one or more boreholes that penetrate 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 vents gas and intersects containers of waste as described with *E2*. 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 head 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 may be incorporated into the Castile brine if it circulates through the waste adjacent to the borehole. If the pressure gradient is not favorable for circulation of Castile brine through the waste, a long-term discharge of Salado brine and waste-generated gas may occur as described in *E2*. Upon reaching the Culebra Dolomite, the waste-bearing brine and gas flows down the hydraulic gradient toward the accessible environment boundary; this pressurized brine and gas 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.

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

Scenario *E1E2* consists of exactly two boreholes that penetrate waste-filled rooms or drifts in the same panel (Figure 4-9). 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 and gas flowing up this borehole. The Castile brine is assumed to be under a greater pressure than gas or brine in rooms and drifts of the repository (Marietta et al., 1989).

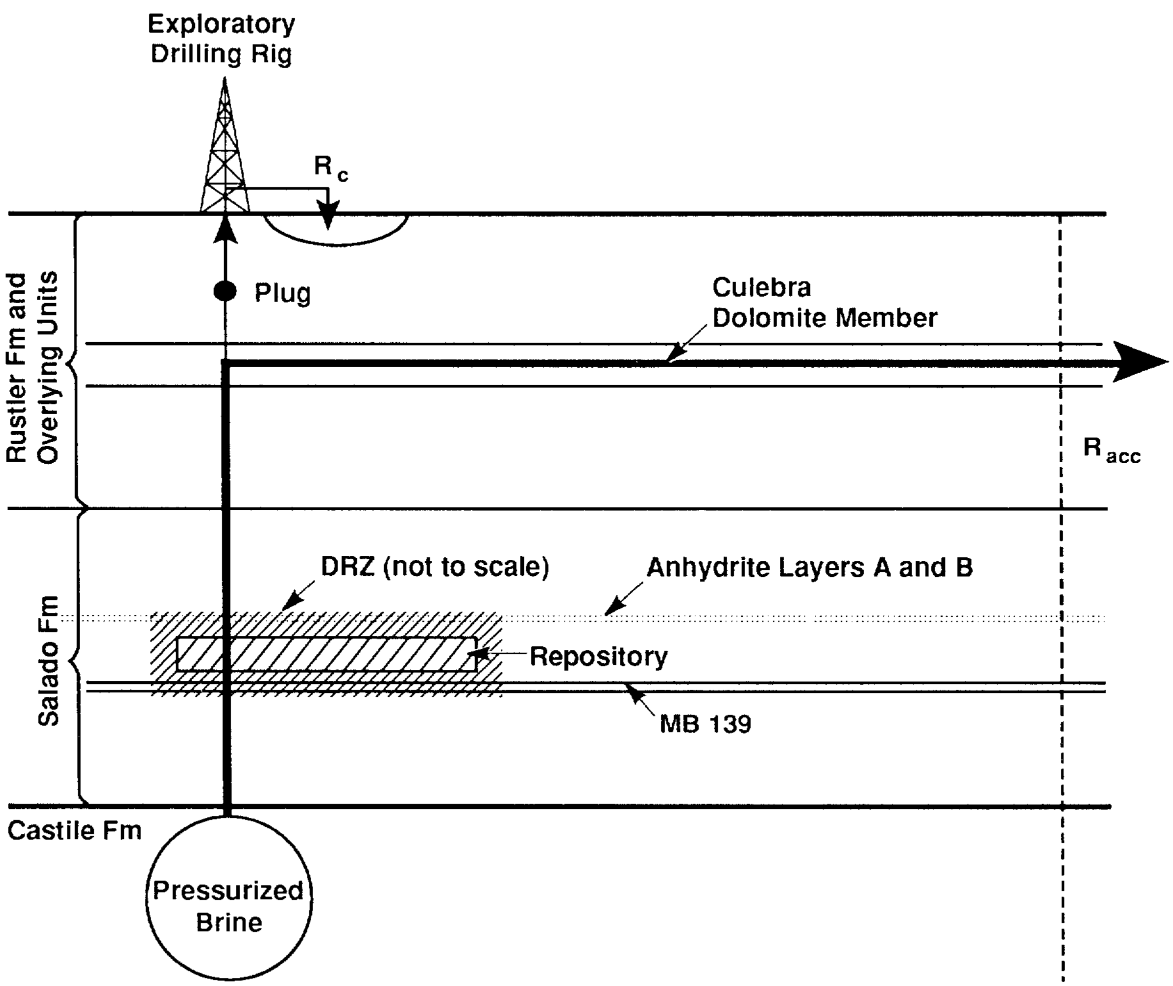

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Figure 4-8. Conceptual Model for Scenario *E1*. Arrows indicate assumed direction of flow. Exploratory borehole penetrates pressurized brine below the repository horizon. R_C is the release of cuttings and eroded material. R_{acc} is the release at the subsurface boundary of the accessible environment. A plug above the Culebra Dolomite Member is assumed to remain intact for 10,000 years.

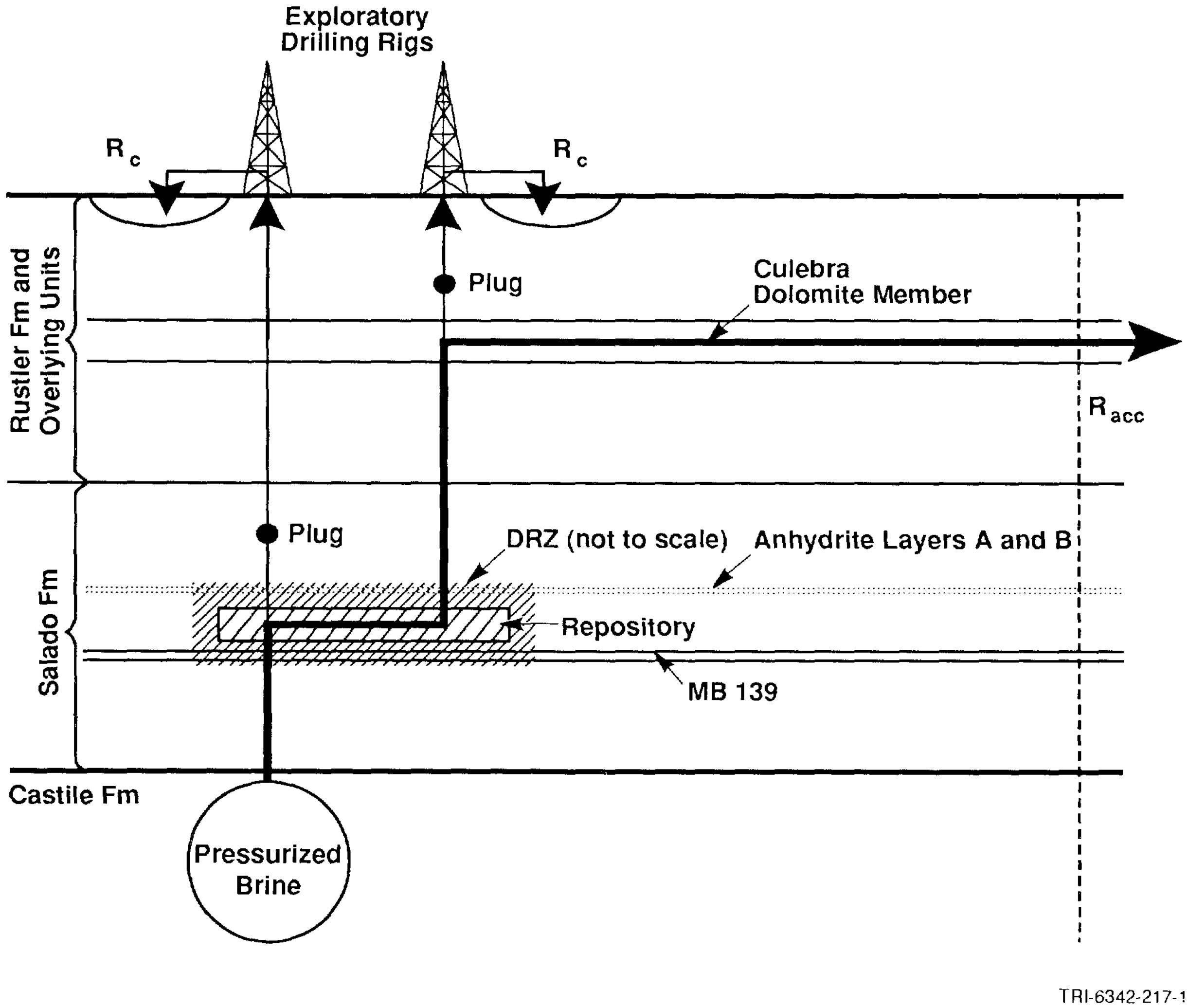

Figure 4-9. Conceptual Model for Scenario *E1E2*. Arrows indicate assumed direction of flow. One exploratory borehole penetrates pressurized brine below the repository horizon and a plug between the repository and the Culebra Dolomite Member is assumed to remain intact for 10,000 years. The second borehole 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.

Radionuclides and gas are released directly to the surface during drilling of the two holes as described with *E1* and *E2*. 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 and gas from the pressurized brine reservoir to flow through waste panels and nearby members 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 brine 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 in Chapter 6 of this volume.

4.1.8 DEFINITION OF COMPUTATIONAL SCENARIOS

A more detailed decomposition of the sample space *S* is desired for the actual calculations that must be performed to determine scenario consequences (i.e., $\mathbf{cS}_i$ as shown in Equation 3-1) and to provide a basis for constructing a family of CCDFs as described earlier. To provide more detail for the determination of both scenario probabilities and scenario consequences, the computational scenarios on which the actual CCDF construction is based for the WIPP performance assessment are defined on the basis of (1) number of drilling intrusions, (2) time of the drilling intrusions, (3) whether or not a single waste panel is penetrated by two or more boreholes, of which at least one penetrates a brine pocket and at least one does not, and (4) the activity level of the waste penetrated by the boreholes. The purpose of this decomposition is to provide a systematic coverage of what might reasonably happen at the WIPP.

The procedure starts with the division of the 10,000-year time period appearing in the EPA regulations into a sequence

$$[t_{i-1}, t_i], \; i = 1, 2, \ldots, nT, \tag{4-8}$$

of disjoint time intervals. When activity loading in the waste panels is not considered, these time intervals lead to computational scenarios of the form

$$S(\mathbf{n}) = \{x\text{: } x \text{ an element of } S \text{ for which exactly } n(i) \text{ intrusions occur in the time interval } [t_{i-1}, t_i],\; i=1,2,\ldots,nT\} \tag{4-9}$$

and

$$S^{+-}(t_{i-1}, t_i) = \{x\text{: } x \text{ an element of } S \text{ involving two or more boreholes that penetrate the same waste panel during the time interval } [t_{i-1}, t_i] \text{, at least one of these boreholes penetrates a pressurized brine pocket and at least one does not penetrate a pressurized brine pocket}\}, \tag{4-10}$$

where

$$\mathbf{n} = [n(1), n(2), \ldots, n(nT)]. \tag{4-11}$$

When activity loading is considered, the preceding time intervals lead to computational scenarios of the form

$$S(\mathbf{l},\mathbf{n}) = \{x\text{: } x \text{ an element of } S(\mathbf{n}) \text{ for which the } j^{th} \text{ borehole encounters waste of activity level } \ell(j)\} \tag{4-12}$$

and

$$S^{+-}(\mathbf{l}; t_{i-1}, t_i) = \{x\text{: } x \text{ an element of } S^{+-}(t_{i-1}, t_i) \text{ for which the } j^{th} \text{ borehole encounters waste of activity level } \ell(j)\}, \tag{4-13}$$

where

$$\mathbf{l} = [\ell(1), \ell(2), \ldots, \ell(nBH)] \text{ and } nBH = \sum_{i=1}^{nT} n(i). \tag{4-14}$$

Further refinements on the basis of whether or not subsidence occurs and whether or not individual boreholes penetrate pressurized brine pockets are also possible. In essence, the computational scenarios defined in Equation 4-8 through Equation 4-14 are defining an importance sampling strategy that covers the stochastic or Type A uncertainty that is characterized by the scenario probabilities pS_i appearing in Equation 3-1. Additional information on the definition of computational scenarios is given in Volume 2, Chapter 3 of this report.

4.2 Determination of Scenario Probabilities

The second element of the ordered triples shown in Equation 3-1 is the scenario probability pS_i. As with the scenarios, these probabilities have been developed at two different levels of detail. The first level is for the summary scenarios discussed in Section 4.1.2-Definition of Summary Scenarios and shown in Figure 4-5. The primary purpose of these probabilities is to provide guidance in scenario development. The development of these probabilities is described in Section 4.2.1-Probabilities for Summary Scenarios. The second level is for the computational scenarios discussed in Section 4.1.8-Definition of Computational Scenarios. These are the probabilities that will actually be used in the construction of CCDFs for comparison with the EPA release limits. These probabilities are defined in Section 4.2.2-Probabilities for Computational Scenarios.

4.2.1 PROBABILITIES FOR SUMMARY SCENARIOS

Probabilities for the summary scenarios described in Section 4.1.2-Definition of Summary Scenarios were estimated as part of a previous 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 these scenarios were reviewed and additional probabilities were estimated by Guzowski (1991), 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) 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. When viewed at a high level, this process involves development of a sample space S, a collection $\mathcal{S}$ of subsets of S, and ultimately, a probability function defined for elements of $\mathcal{S}$. The status and preliminary results of effort are described in the final section of this chapter. 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 for the summary scenarios are based on the current understanding of natural resources in the vicinity of the repository, projections of future drilling activity, and regulatory guidance. Two sets of probability estimates (Marietta et al., 1989; Guzowski, 1991) were compared by Bertram-Howery et al. (1990). Neither set was considered credible enough to be used as final probability estimates in the absence of formal expert-judgment elicitation (Guzowski, 1991). Both sets of preliminary probabilities, derived by using different probability techniques, were used in the 1990 preliminary assessment, and the resultant comparison of simulated performances provided a measure of the sensitivity of the modeling system to the uncertainty in scenario probability assignment. One set, obtained 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, 1991). The scenario probabilities can be estimated from the logic diagram as before (Figure 4-10). 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 4-11). The probability of human intrusion is 0.01 for the first set and 0.24 for the second set.

4.2.2 PROBABILITIES FOR COMPUTATIONAL SCENARIOS

Probabilities for the computational scenario refinements are now presented. These are the probabilities that will be used in the construction of CCDFs for comparison with the EPA release limits in the present report. These probabilities are based on the assumption that the occurrence of boreholes through the repository follows a Poisson process with a rate constant λ. The probabilities $pS(\mathbf{n})$ and $pS(\mathbf{l},\mathbf{n})$ for the computational scenarios $S(\mathbf{n})$ and $S(\mathbf{l},\mathbf{n})$ are given by

$$pS(\mathbf{n}) = \left\{ \prod_{i=1}^{nT} \left[\frac{\lambda^{n(i)} \left(t_i - t_{i-1}\right)^{n(i)}}{n(i)!} \right] \right\} \exp\left[-\lambda \left(t_{nT} - t_0 \right) \right] \tag{4-15}$$

and

$$pS(\mathbf{l},\mathbf{n}) = \left\{ \prod_{j=1}^{nBH} pL_{\ell(j)} \right\} pS(\mathbf{n}), \tag{4-16}$$

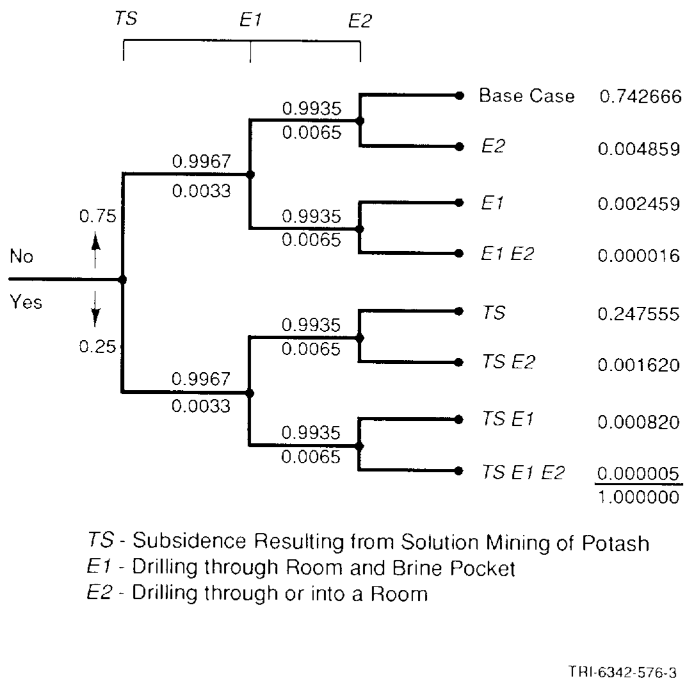

Figure 4-10. Scenario Probability Estimate Based on Guzowski (1991).

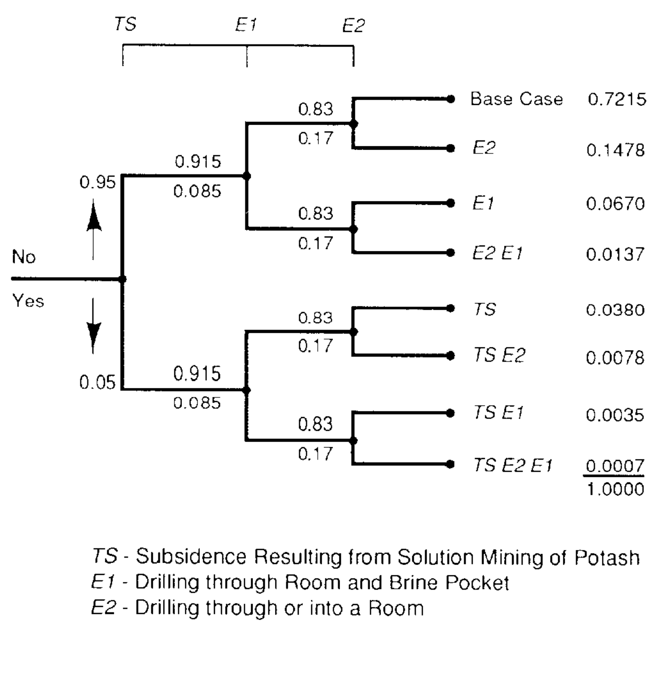

Figure 4-11. Scenario Probability Estimate Based on Marietta et al.(1989).

where **n** and **l** are defined in Equations 4-11 and 4-14, respectively, and pL_ℓ is the probability that a randomly placed borehole through a waste panel will encounter waste of activity level ℓ. The rate constant λ is a sampled variable in the 1991 WIPP performance assessment. Table 3-2 provides an example of probabilities $pS(\mathbf{n})$ calculated as shown in Equation 4-15 with $\lambda = 3.28 \times 10^{-4}\ \mathrm{yr}^{-1}$, which corresponds to the maximum drilling rate suggested for use by the EPA. The activity level probabilities pL_ℓ used in the 1991 WIPP performance assessment are presented in Table 4.3.

The probabilities $pS^{+-}(t_{i-1},t_i)$ and $pS^{+-}(\mathbf{l};t_{i-1},t_i)$ for the computational scenarios $S^{+-}(t_{i-1},t_i)$ and $S^{+-}(\mathbf{l};t_{i-1},t_i)$ are given by

$$pS^{+-}(t_{i-1},t_i) = \sum_{\ell=1}^{nP} \{1 - \exp[-\alpha(\ell)(t_{i-1},t_i)]\}\ \{1 - \exp[-\beta(\ell)\ (t_{i-1},t_i)]\} \tag{4-17}$$

and

$$pS^{+-}(\mathbf{l};t_{i-1},t_i) = \left[\prod_{j=1}^{nBH} pL_{\ell(j)}\right] pS^{+-}(t_{i-1},t_i), \tag{4-18}$$

where

$$\alpha(\ell) = \frac{[aBP(\ell)]\lambda}{aTOT}$$

$$\beta(\ell) = \frac{[aTOT(\ell) - aBP(\ell)]\lambda}{aTOT}$$

$aBP(\ell)$ = area (m^2) of pressurized brine pocket under waste panel ℓ,

$aTOT(\ell)$ = total area (m^2) of waste panel ℓ,

$aTOT$ = total area (m^2) of waste panels,

and

nP = number of waste panels.

The probability $pS^{+-}(t_{i-1},t_i)$ can also be determined under the assumption that exactly two boreholes are involved (see Chapter 2, Volume 2 of this report).

The relations appearing in Equations 4-15 through 4-18 are derived in Volume 2, Chapter 2 of this report under the assumption that drilling intrusions follow a Poisson process (i.e., are random in time and space). The

TABLE 4-3. ACTIVITY LEVELS AND ASSOCIATED PROBABILITIES USED IN 1991 WIPP PERFORMANCE ASSESSMENT

Activity Level	Type[a]	Probability[b]	Time (years) 0	1000	3000	5000	7000	9000
1	CH	0.4023	3.4833	0.2718	0.1840	0.1688	0.1575	0.1473
2	CH	0.2998	34.8326	2.7177	1.8401	1.6875	1.5748	1.4729
3	CH	0.2242	348.326	27.177	18.401	16.875	15.748	14.729
4	CH	0.0149	3483.26	271.77	184.01	168.75	157.48	147.29
5	RH	0.0588	117.6717	0.1546	0.1212	0.1139	0.1082	0.1030
Average for CH Waste:			150.7905	11.7648	7.9658	7.3053	6.8174	6.3764

[a] CH designates contact handled waste; RH designates remote handled waste

[b] Probability that a randomly placed borehole through the waste panels will intersect waste of activity level ℓ, ℓ = 1,2,3,4,5.

derivations are quite general and include both the stationary (i.e., constant λ) and nonstationary (i.e., time-dependent λ) cases.

4.3 Expert Judgment on Inadvertent Human Intrusion

Identifying the probability of future inadvertent human intrusion is at best a qualitative task. 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, organized into two separate panels, to address possible modes of inadvertent intrusion and types of markers to deter intrusion. These experts evaluate the available information, reduce the problems to manageable components, and with the assistance of probability specialists, quantify 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.

The activities and results of the future-intrusion panel are discussed here. The planned marker-development panel is discussed in Chapter 8 of this volume.

4.3.1 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 with necessary background information and an explicit statement of the issue or issues 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 enhance decomposition and analysis of the questions. Individuals knowledgeable in both the topic under discussion and expert elicitation quantify the responses from each expert.

4.3.2 EXPERT SELECTION

Expert selection for the future-intrusion panel was a major activity. Sixteen experts organized into four four-member teams were selected. Their backgrounds span a variety of social and physical sciences including, for example, futures studies, demography, mining engineering, agricultural science, and resource economics. 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 panel 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. Once the nominators were identified (71 individuals), they were formally requested to nominate candidates for the panel.

The nominators, who could also nominate themselves, submitted a total of 126 nominations. The nominees were requested to submit a description of their interests and any special qualifications relevant to this activity, along with a curriculum vitae. Letters of interest were received from 70 nominees.

The selection committee for this panel was composed of three individuals who are not members of the SNL staff. Each member of the selection committee 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 among team members; and balance among all participants to ensure adequate representation of various constituent groups.

4.3.3 EXPERT-JUDGMENT ELICITATION

The future-intrusion experts were 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, to 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 were asked to identify and quantify expected modes of intrusion into the repository and to examine 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.

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 climate 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.

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[1] The expert-elicitation scenarios are referred to here as "futures" to avoid confusion with scenarios developed for consequence analysis.

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 have provided written reports that discuss societal development, describe possible futures, and establish the basis for estimating the possibilities of these futures. The teams have analyzed modes of intrusion and developed probabilistic quantitative estimates of the frequencies of various intrusions. The likelihoods of various futures were also estimated by the teams with assistance from an elicitation specialist. The results of the elicitation sessions and the subsequent analysis were returned to the panelists for review and comment. A more detailed description of this process and the results can be found in Hora et al. (1991).

4.3.4 PANEL RESULTS

The material provided by the four teams falls into two categories: qualitative discussions of the future states of society and modes of intrusion found in the reports provided by each team; and a more quantitative analysis developed during the elicitation sessions. The teams were given complete freedom in addressing the issue statement, so all utilized different approaches. One important reason for convening the future-intrusion panel was to provide input to the marker-development panel regarding modes of intrusion and states of society that should be considered when examining markers to deter inadvertent human intrusion (providing design characteristics and estimating effectiveness). As such, the panelists were not limited in the issue statement to considering the mode of intrusion specified by the Standard and now being modeled—intrusion by a borehole. Thus, some modes of intrusion discussed by the teams cannot currently be modeled by computer programs.

A qualitative description of the various futures developed by the teams is presented here. The actual reports written by the four teams are reproduced as appendices in Hora et al. (1991).

Boston Team

The probability assessment developed by the Boston Team (T. Gordon, M. Baram, W. Bell, and B. Cohen) assigned probabilities to particular modes of human intrusion. They started with descriptions of possible future societies and worked forward to develop possible modes of intrusion. This resulted in six specific modes of intrusion, four of which involve activities that directly impact the WIPP (disposal of wastes through injection wells, drilling for resources, underground storage of additional nuclear waste at the WIPP, and archaeological exploration), and two others that would have an indirect impact (the construction of dams and explosive testing in the area). Whether or not the intrusion would take place was believed to be influenced by five underlying factors (level of technology, world population, cost of materials, the persistence of knowledge concerning the WIPP, and the level of industrialization in the WIPP area). In addition, the team felt that the 10,000 year period of regulatory interest should be further divided (years 0 to 300, 300 to 3000, and 3000 to 10,000) and that factors and probabilities would be different during these intermediate periods. The Boston Team provided numerous conditional probabilities that captured all the interactions between the underlying factors and the three time periods in order to develop specific intrusion probabilities or frequencies.

Southwest Team

In contrast to the Boston Team, whose analysis was very specific and detailed, the Southwest Team (G. Benford, C. Kirkwood, H. Otway, and M. Pasqualetti) chose to focus on two broad societal factors that they felt influenced the probability of human intrusion at the WIPP, without directly linking the probability to a particular mode of intrusion. Political control, whether by the United States or by some other country, was seen as quite important, especially with regards to active control of the site and the continuation of information regarding the exact location and dangers of the WIPP. The other important underlying factor is that of the pattern of technological development (a steady increase, a steady decrease, or a seesaw between high and low levels of technology). Technological development relates to the ability to intrude upon the WIPP and to detect various warnings. While this team did not divide the 10,000 year regulatory period for the actual probability calculation, they did state that the probability of altered political control is high over the next 200 years. They also gave periods for each of the three patterns during which intrusion would be most likely (steady increase: 1000 to 2000 years; steady decrease: 100 to 500 years; and seesaw: cycles of 1000 years). This strategy resulted in a single probability of inadvertent human intrusion over the 10,000 year regulatory period. The probability is of one intrusion, for they thought that multiple intrusions were unlikely.

Several questions were handled by the team outside of the direct probability elicitation. Depending on the technological development pattern, modes of intrusion might include mole miners, nanotechnology, and deep strip mining for steady increase, or conventional drilling and excavation for steady decline and seesaw. The question of whether the wastes would be rendered harmless was given a probability of 0.99 in the steady-increase pattern, and essentially a zero probability for the other two patterns.

Washington A Team

The Washington A Team (D. Chapman, V. Ferkiss, D. Reicher, and T. Taylor) organized their analysis by considering four alternative futures for society. The four futures are (1) continuity, where trends in population growth, technology development, and resource exploration and extraction continue along current lines; (2) radical increase, where current activities continue, but at an increased rate; (3) discontinuity, where there are shifts in political power and socioeconomic development, with a resulting loss of knowledge about the WIPP; and (4) steady-state resources, where current trends in resource extraction and consumption are reversed—recycling of resources and using renewable energy sources—so there is less need to search the earth for extractable resources. Society need not continue with one condition for the entire 10,000 years but may shift among them. Human intrusion is expected to be moderated by active controls at the WIPP (the team assumed no intrusion if there are active controls at the WIPP) and effective information regarding the location and risks of the repository. The probability of intrusion was computed separately for the two time periods of 0 to 200 years and 200 to 10,000 years and assuming that society did not shift among conditions. The first period was thought to be crucial except for the steady-state condition.

The two probabilities developed were not linked to particular modes, but the team did discuss both direct (deep tunnel that intersects the WIPP, drilling, and excavation) and indirect (dams, a water-well field, and explosions) activities that might intrude upon the repository. They also outlined which modes they thought were likely to take place with the four alternative futures: conventional drilling and excavation with the continuity future; conventional drilling and excavation, machine mining, and tunnels or pipelines with the radical-increase future; conventional drilling and excavation with the discontinuity future; and indirect means with the steady-state future.

Washington B Team

The Washington B Team (T. Glickman, N. Rosenberg, M. Singer, and M. Vinovskis) started with four specific modes of intrusion (resource exploration and extraction, development of groundwater, scientific investigation, and weather modification) that were thought to be influenced by four underlying factors in society (the overall level of wealth and technology, prudent and effective government control, climate, and resource prices). Two significant periods of time were used in the calculations: the near future (0 to 200 years) and the far future (200 to 500 years for resource exploration and extraction, and 200 to 10,000 years for the other three modes). There were differences in the applicable underlying factors for both the modes of intrusion and the time periods, and different conditional probabilities describing the interactions between the factors. Thus, separate probabilities of intrusion were calculated for each mode and for each time period.

The findings of the future-intrusion panel were not incorporated into the 1991 calculations. Efforts are currently being made to organize the results so that they can be used in the 1992 calculations.

Chapter 4—Synopsis

Scenarios in Performance Assessment

The Containment Requirements of the Standard refer to all significant events and processes that might affect a disposal system.

For a performance assessment to be complete, combinations of events and processes (scenarios) also must be analyzed.

In order to determine compliance with the Containment Requirements,

> the set of scenarios must describe all reasonably possible, potentially disruptive future states of the disposal system,
>
> scenarios must be mutually exclusive,
>
> the consequences of each scenario must be determined,
>
> the probability of occurrence of each scenario must be estimated.

Certain events and processes can be excluded from performance-assessment analyses based on low probability and/or low consequence of occurrence.

Identifying Events and Processes

The WIPP performance-assessment team has adopted and modified a generic list of events and processes that could affect the performance of a waste-disposal facility.

Phenomena that occur instantaneously or within a relatively short time interval are considered events. Phenomena that occur over a significant portion of the 10,000 years of regulatory concern are considered processes.

Screening Events and Processes

Events and processes are screened based on probability of occurrence, physical reasonableness, and consequence.

Events and processes with less than one chance in 10,000 of occurring in 10,000 years do not have to be considered.

Sufficient data may not be available to calculate a probability of occurrence. A logical argument based on physical reasonableness can establish whether conditions exist or can change to a sufficient degree within the regulatory time period for a particular event or process to occur with sufficient magnitude to affect the performance of the disposal system.

Consequence is based on whether the event or process, either alone or in combination with other events or processes, may affect the performance of the disposal system.

Natural Events or Processes

None of the potentially disruptive natural events or processes considered for the WIPP were retained for scenario development of disturbed performance.

Events or processes that are part of the base-case scenario are

- erosion,
- sedimentation,
- climatic change (pluvial periods),
- seismic activity,
- shallow dissolution (Rustler-Salado contact residuum).

Events or processes that were eliminated from consideration based on low probability of occurrence are

- meteorite impact,
- tsunamis (from meteorite impacts),
- shallow dissolution (depending on theory).

Events or processes that were eliminated from consideration based on physical unreasonableness arguments are

- glaciation,
- hurricanes,
- seiches,
- tsunamis (of traditional origin),
- regional subsidence or uplift,
- mass wasting,
- flooding,
- diapirism,
- volcanic activity,
- magmatic activity,
- deep dissolution,
- shallow dissolution (depending on theory),
- faulting.

Because sea-level variation is dependent on other events or processes, it is not considered as an independent phenomenon for scenario development.

Human-Induced Events or Processes

Events or processes that were eliminated from consideration based on low probability of occurrence are

- accidental surface and near-surface nuclear explosions during warfare,

- damming of streams and rivers.

Events or processes that were eliminated from consideration based on physical unreasonableness are

- nuclear testing or enhanced oil recovery using nuclear devices,

- irrigation.

Events or processes that were eliminated from consideration based on low consequence are

- injection wells,

- drilling of deep oil or gas wells outside the WIPP boundaries.

Evaluation of deliberate, large-scale nuclear explosions at the WIPP is not required by the Standard.

Events or processes that are being evaluated for inclusion in disruptive scenarios because of their possible effects on groundwater flow are

potash mining (outside the boundaries of the waste panels),

drilling of water wells,

drilling of oil or gas exploratory wells.

Exploratory drilling for resources is a realistic event for the WIPP and is retained for two possibilities of scenario development:

drilling into a waste-filled room or drift, with a brine reservoir in the underlying Castile Formation,

drilling into a waste-filled room or drift without breaching a brine reservoir.

Repository- and Waste-Induced Events or Processes

Events or processes that were eliminated from consideration based on physical unreasonableness are

thermally induced stress fracturing in the host rock,

explosions because of nuclear criticality.

Events or processes that were eliminated from consideration based on low consequence are

caving and subsidence,

explosions or fires within waste-filled rooms and drifts.

Events or processes that are part of the base-case scenario are

shaft-seal degradation,

excavation-induced stress fracturing in the host rock,

gas generation within the repository.

A phenomenon that is being evaluated for inclusion in the development of disruptive scenarios is heat generated by nuclear criticality.

Developing Scenarios

Scenarios used in performance assessment must be comprehensive and mutually exclusive.

The WIPP performance assessment uses a logic diagram to construct scenarios. 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. 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 data base. Each scenario consists of a combination of occurrence and nonoccurrence of all events and processes that survive screening.

Screening Scenarios

Scenarios are screened to identify those that have little or no effect on the mean CCDF.

Scenarios are screened on the same criteria used to screen events and processes: physical reasonableness, probability of occurrence, and consequence.

The probability of occurrence of a scenario is determined by combining the probability of occurrence and nonoccurrence of its constituent events and processes.

Descriptions

Undisturbed Performance Scenario

The undisturbed performance scenario includes all natural events and processes expected to occur at the WIPP during the next 10,000 years. It also includes undisturbed processes within the disposal system, such as gas generation within the waste panels.

The undisturbed performance scenario is used to evaluate compliance with the Individual Protection Requirements and as the base-case scenario for assessments of disturbed performance for evaluation of compliance with the Containment Requirements.

Human-Intrusion Scenarios

Three summary human-intrusion scenarios are considered:

*E*2, in which a borehole penetrates a waste panel, creating a flow path to the Culebra Dolomite,

*E*1, in which a borehole penetrates a waste panel and an underlying pressurized brine reservoir in the Castile Formation, creating a flow path to the Culebra Dolomite, *E1E2*, in which two boreholes, one of each type, penetrate a single waste panel, creating a flow path for Castile brine through the waste from one hole to the other and then upward to the Culebra Dolomite.

Scenario Probability Assignments

Probabilities for the 1991 computational scenarios are based on the assumption that intrusion follows a Poisson process (i.e., boreholes are random in time and space) with a rate constant, λ, that is sampled as an uncertain parameter in the 1991 calculations.

Expert Judgment on Inadvertent Human Intrusion

The WIPP Project has selected panels of external experts to provide judgment for use in determining the probability of intrusion.

One panel has met and has addressed the possible modes of intrusion and their likelihoods.

A second panel will be convened to address types of markers that could deter intrusion, thereby lowering its probability.

Techniques of Expert-Judgment Elicitation

Judgments are elicited from experts in quantitative probabilistic forms suitable for use in performance assessments.

Expert Selection

Experts for the future-intrusion panel were selected with a three-step process:

seventy-one nominators were identified through literature searches and contacts with professional organizations, government organizations, and private industry,

one hundred and twenty six nominees were identified, of whom seventy expressed interest,

sixteen panel members were selected on the basis of expertise, professional reputation, availability and willingness to participate, understanding of the problem, impartiality, lack of an economic or personal stake in the outcome, balance of expertise, physical proximity to other panel members, and balance among various constituent groups.

Expert-Judgment Elicitation

The future-intrusion experts were asked to identify reasonable, foreseeable futures for human societies, to suggest how these futures could result in intrusions, and to provide probabilities for their futures.

Panel Results

Each of four teams on the future-intrusion panel identified possible futures and the associated probabilities of intrusion.

Findings of the panel are still being analyzed and were not incorporated into the 1991 calculations.

5. COMPLIANCE-ASSESSMENT SYSTEM

[NOTE: The text of Chapter 5 is followed by a synopsis that summarizes essential information, beginning on page 5-73.]

This chapter reviews the conceptual models used for quantitative simulations of the disposal system. A full documentation of the compliance-assessment system is beyond the scope of a single chapter, and wherever possible the reader is referred to original documents for technical details. Descriptions of specific computer programs and their applications to the WIPP performance assessment have been included in Volume 2 of this report, and are described here only briefly. Additional information about the executive controller for the computer programs within the modeling system can be found in Rechard et al. (1989). Data used in the 1991 preliminary performance assessment are available in Volume 3 of this report.

The first two major sections of this chapter describe the physical components of the disposal system and its surroundings that will provide barriers to radionuclide migration during the next 10,000 years. These barriers are of two types: natural barriers, which are features of the regional and local environment, and engineered barriers, which include designed features of the repository system, such as the panel and shaft seals. Descriptions of the physical components are followed by qualitative descriptions of the models used to simulate performance of the barrier systems.

The third section of the chapter briefly describes CAMCON, the Compliance Assessment Methodology Controller. CAMCON is the executive program which links specific numerical models into a single computational system capable of generating the Monte Carlo simulations required for probabilistic performance assessments.

5.1 The Natural Barrier System

The hydrogeologic setting of the WIPP provides excellent natural barriers to radionuclide migration. Groundwater flow, which provides the primary mechanism for radionuclide migration from the WIPP, is extremely slow in the host Salado Formation, and is slow enough in the overlying rocks to be of concern during the next 10,000 years only in the most transmissive units. If radionuclides reach the overlying units, geochemical retardation during transport may provide an additional barrier to migration.

5.1.1 REGIONAL GEOLOGY

The geology of the WIPP and the surrounding area has been summarized in Chapter 1 of this volume, and is described elsewhere in detail (e.g., Powers et al., 1978a,b; Cheeseman, 1978; Williamson, 1978; Hiss, 1975; Hills, 1984; Harms and Williamson, 1988; Ward et al., 1986; Holt and Powers, 1988; Beauheim and Holt, 1990; Brinster, 1991). The brief review presented here describes regional structural features and introduces the major stratigraphic units. Specific geologic features that affect compliance-assessment modeling are described in greater detail in subsequent sections of this chapter.

The WIPP is located in the Delaware Basin, a structural depression that formed during the Late Pennsylvanian and Permian Periods, approximately 300 to 245 million years ago (Figures 5-1, 5-2). Sedimentation within the subsiding basin resulted in the deposition of up to 4,000 m (13,000 ft) of marine strata. Organic activity at the basin margins produced massive carbonate reefs that separated deep-water facies from the shallow-water shelf sediments deposited landward.

Permian-age rocks of importance to WIPP performance-assessment modeling are those of the Guadalupian and Ochoan Series, deposited between approximately 265 and 245 million years ago (Figure 5-3). During this time subsidence in the Delaware Basin was initially rapid, resulting in deposition of deep-water shales, sandstones, and limestones of the Delaware Mountain Group. Intermittent connection with the open ocean and a decrease in clastic sediment supply, possibly in response to regional tectonic adjustments, led to the deposition of a thick evaporite sequence. Anhydrites and halites of the Castile Formation are limited to the structurally deeper portion of the basin, enclosed within the reef-facies rocks of the Capitan Limestone. Subsidence within the basin slowed in Late Permian time, and the halites of the Salado Formation, which include the host strata for the WIPP, extend outward from the basin center over the Capitan Reef and the shallow-water shelf facies. Latest Permian-age evaporites, carbonates, and clastic rocks of the Rustler Formation and the Dewey Lake Red Beds record the end of regional subsidence and include the last marine rocks deposited in southeastern New Mexico. The overlying sandstones of the Triassic-age Dockum Group reflect continental deposition and mark the onset of a period of regional tectonic stability that lasted approximately 240 million years, until late in the Tertiary Period.

Permian-age strata of the Delaware Basin now dip gently (generally less than 1°) to the east, and erosion has exposed progressively older units toward the western edge of the basin (Figures 5-1, 5-4). This tilting reflects the late Pliocene and early Pleistocene (approximately 3.5 million to 1 million years ago) uplift of the Capitan Reef to form the Guadalupe Mountains more than

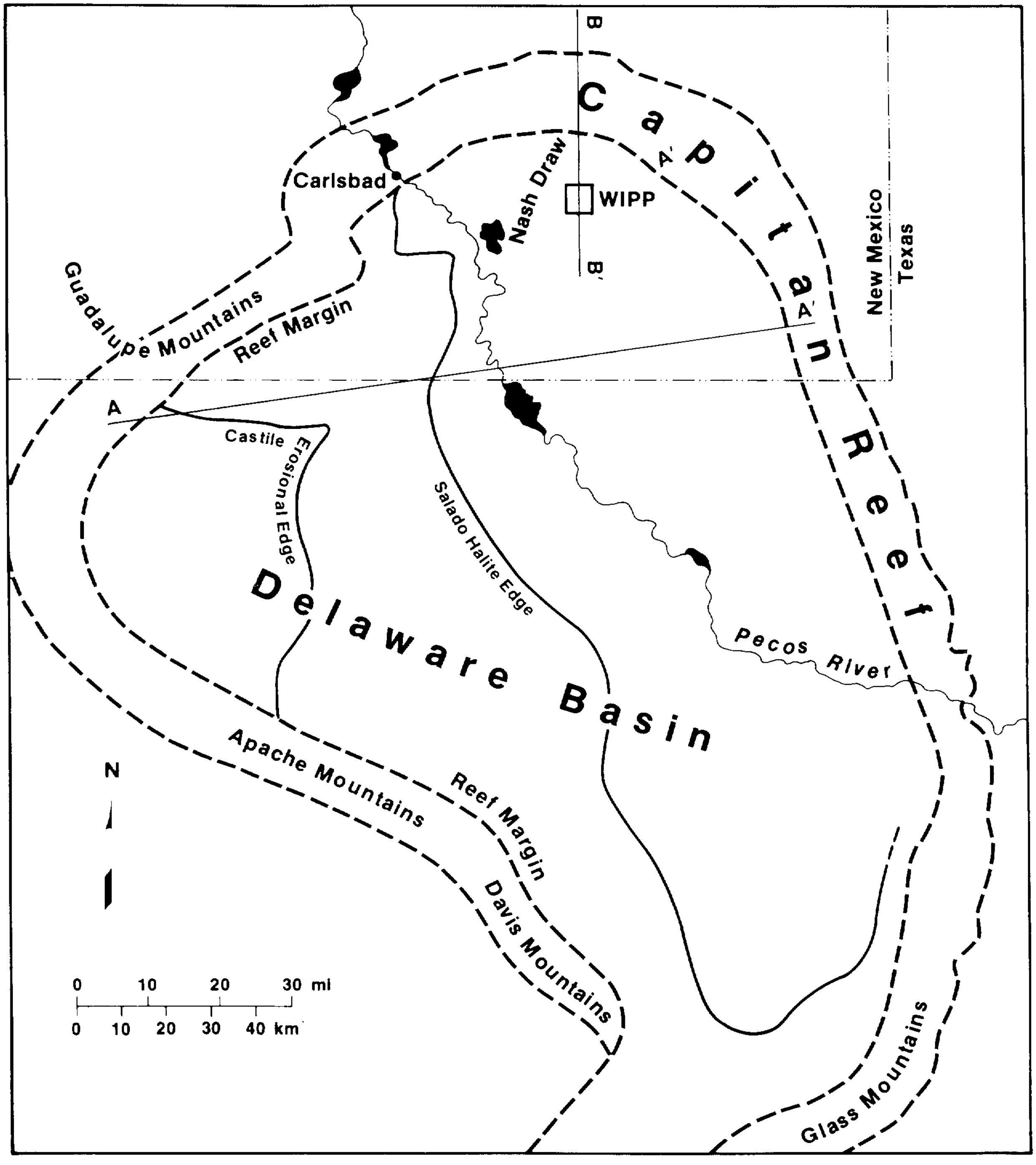

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Figure 5-1. Generalized Geology of the Delaware Basin, Showing the Location of the Capitan Reef and the Erosional Limits of the Basinal Formations (Lappin, 1988).

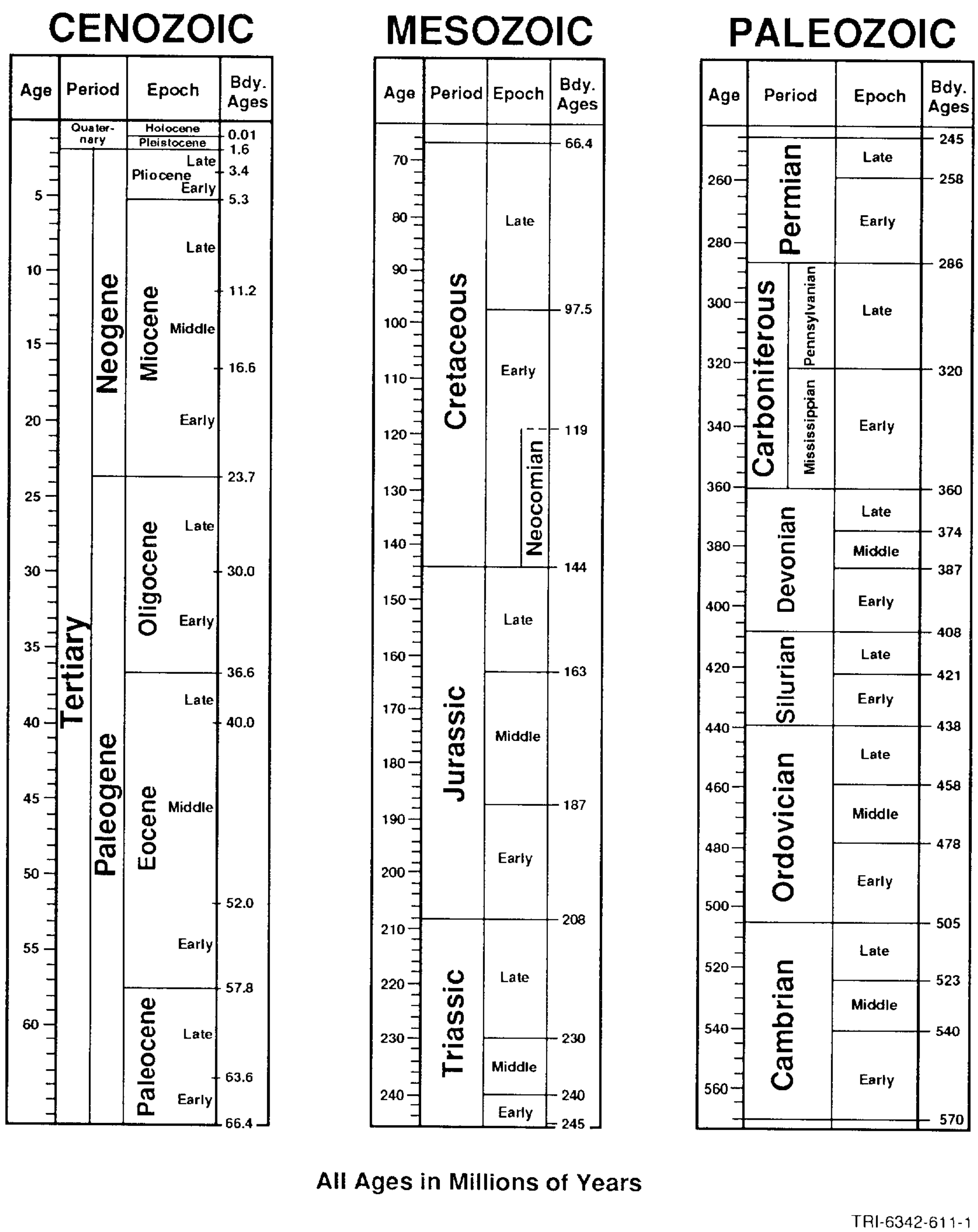

Figure 5-2. Geologic Time Scale (simplified from Geological Society of America, 1984).

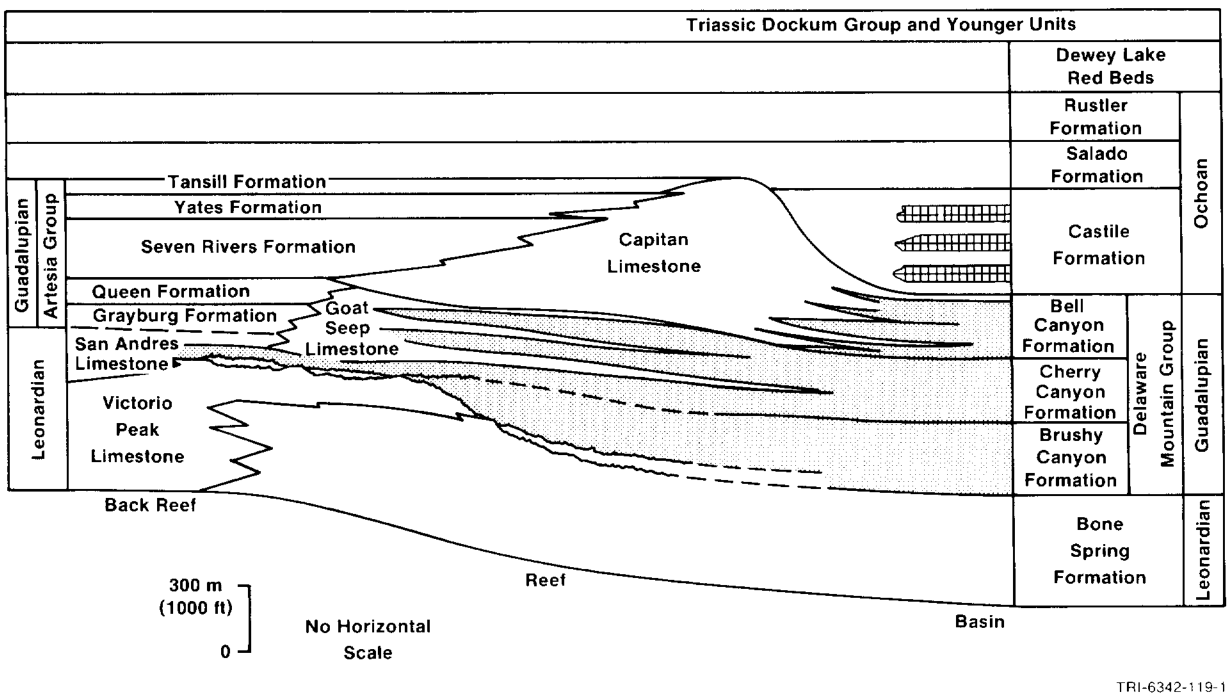

Figure 5-3. Stratigraphy of the Delaware Basin (modified from Mercer, 1983; Brinster, 1991).

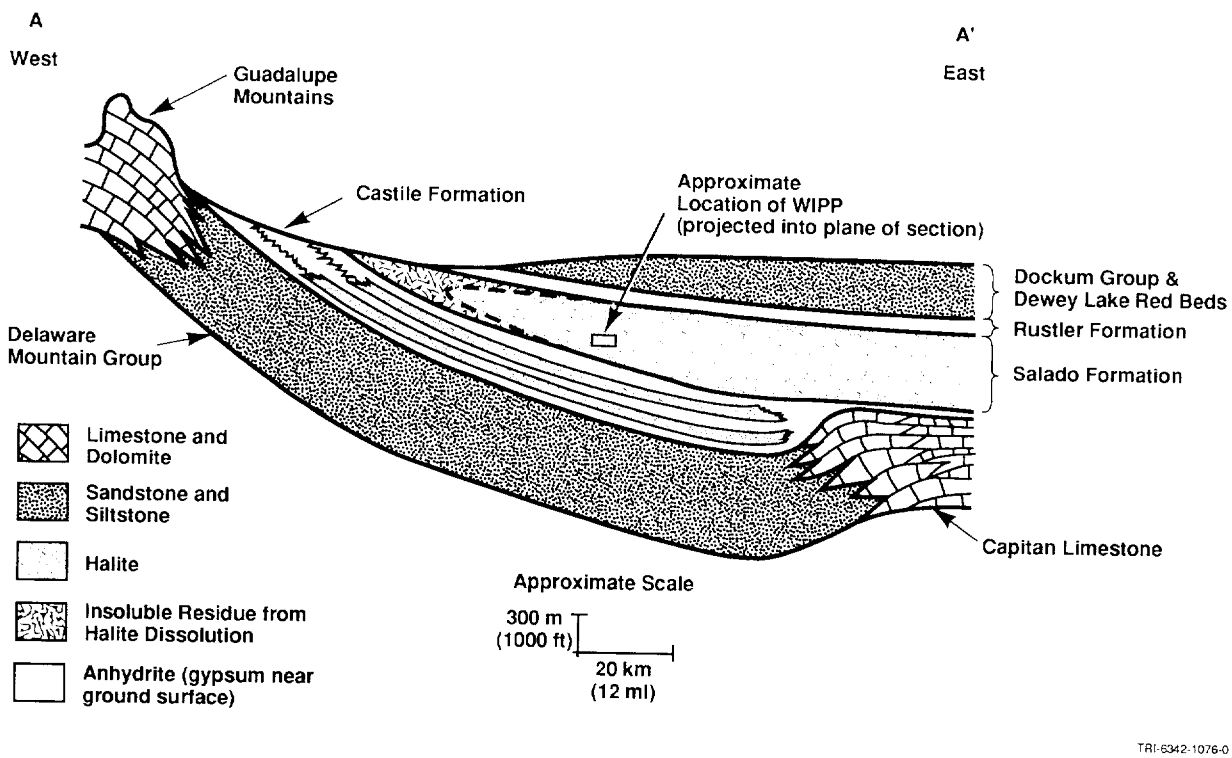

Figure 5-4. Schematic East-West Cross Section through the Northern Delaware Basin (modified from Davies, 1984). Note extreme vertical exaggeration. Approximate location of line of section shown on Figure 5-1.

60 km (37 miles) west of the WIPP (Figures 5-1, 5-4). Field evidence suggests that additional uplift may have occurred during the late Pleistocene and Holocene, and some faults of the Guadalupe Mountains may have been active within the last 1,000 years (Powers et al., 1978a,b). North and east of the WIPP the Capitan Reef has not been uplifted and remains in the subsurface (Figure 5-5).

The present landscape of the Delaware Basin has been influenced by near-surface dissolution of the evaporites (Bachman, 1984, 1987). Karst features created by dissolution include sinkholes, subsidence valleys, and breccia pipes. Most of these features formed during wetter climates of the Pleistocene, although active dissolution is still occurring wherever evaporites are exposed at the surface. Some dissolution may also be occurring at depth where circulating groundwater comes in contact with evaporites: modern subsidence in San Simon Swale east of the WIPP (Figure 1-6) may be related to localized dissolution of the Salado Formation (Anderson, 1981; Bachman, 1984; Brinster, 1991). Nash Draw, which formed during the Pleistocene by dissolution and subsidence, is the most prominent karst feature near the WIPP. As discussed again in Section 5.1.2-Stratigraphy below, evaporites in the Rustler Formation have been affected by dissolution near Nash Draw.

The largest karst feature in the Delaware Basin is the Balmorhea-Loving Trough, south of the WIPP along the axis of the basin (Figure 1-6). Dissolution of evaporites, perhaps along the course of a predecessor of the modern Pecos River, resulted in subsidence and the deposition of Cenozoic alluvium up to 300 m (984 ft) thick in southern Eddy County, and up to almost 600 m (1970 ft) thick across the state line in Texas (Bachman, 1984, 1987; Brinster, 1991).

5.1.2 STRATIGRAPHY

The stratigraphic summary presented here is based on the work of Brinster (1991) and is limited to those units that may have an important role in future performance of the disposal system. Hydrologic data about the units have been summarized by Brinster (1991), and are, in general, not repeated here. Stratigraphic relationships between the units are shown in Figure 5-3. Figure 5-6 shows the region examined in detail by Brinster (1991) and the location of wells that provide basic data.

Bell Canyon Formation

The Bell Canyon Formation consists of 210 to 260 m (690 to 850 ft) of sandstones and siltstones with minor limestones, dolomites, and conglomerates (Williamson, 1978; Mercer, 1983; Harms and Williamson, 1988). Sandstones

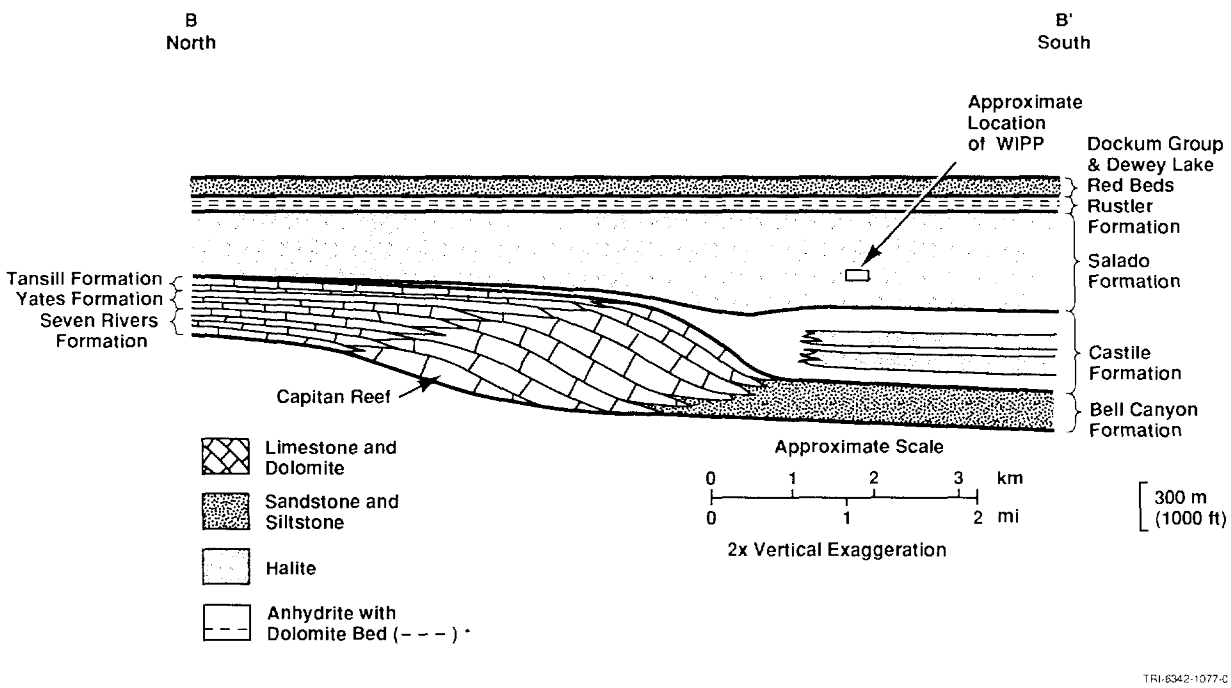

Figure 5-5. Schematic North-South Cross Section through the Northern Delaware Basin (modified from Davies, 1984). Note extreme vertical exaggeration. Approximate location of line of section shown on Figure 5-1.

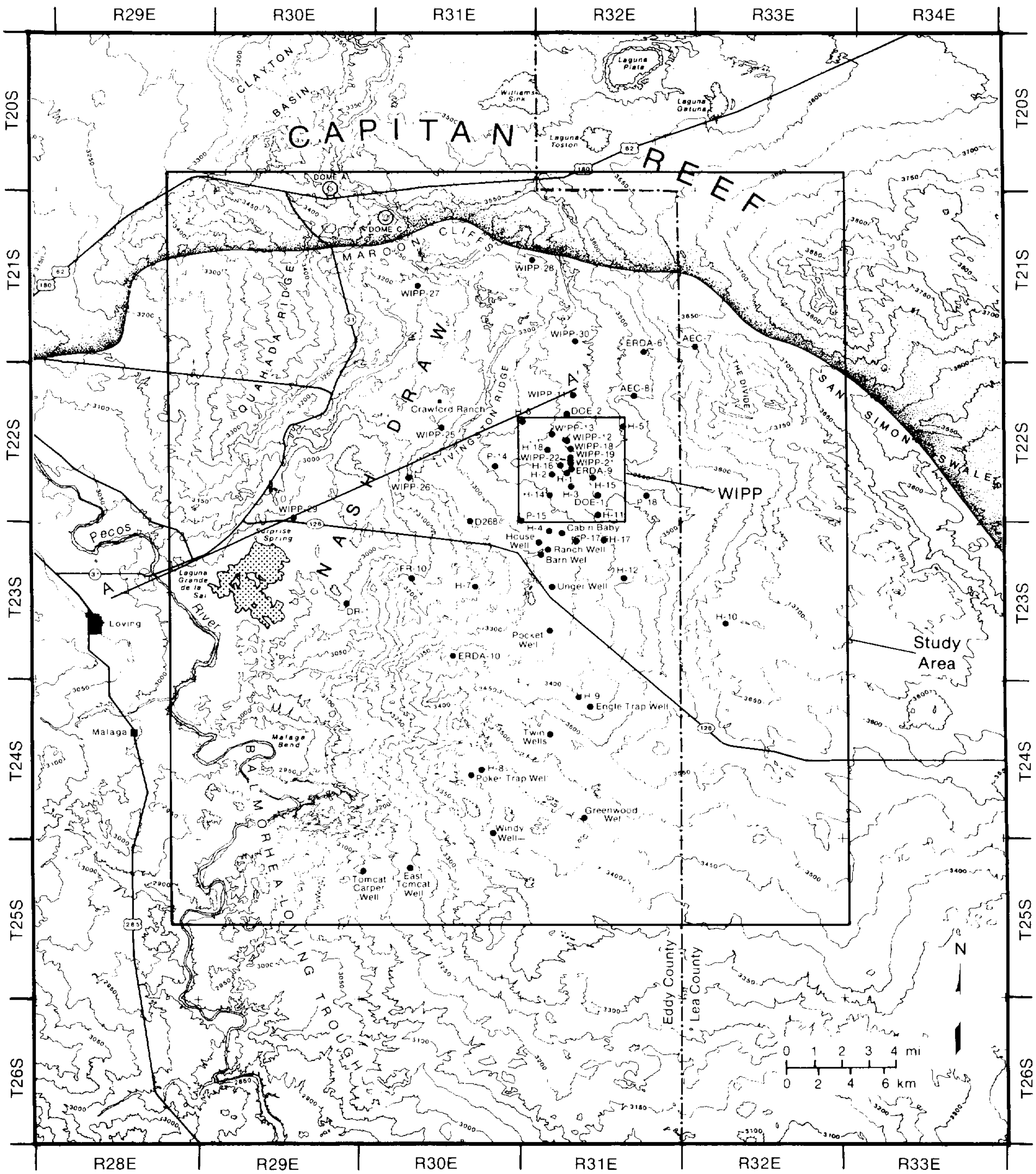

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Figure 5-6. Map of the WIPP Vicinity Showing the Proposed Land-Withdrawal Area, the Study Area of Brinster (1991), and the Location of Observation Wells (Haug et al., 1987; Brinster, 1991).

within the upper portion of the Bell Canyon Formation occur as long, sinuous channels separated by siltstones, reflecting their deposition by density currents that flowed into the deep basin from the Capitan Reef (Harms and Williamson, 1988). These sandstones have been targets for hydrocarbon exploration elsewhere in the Delaware Basin and are of interest for the WIPP performance assessment because they are the first units containing extensive aquifers below the evaporite sequence that hosts the repository.

Simulations of undisturbed repository performance do not include the Bell Canyon Formation because a thick sequence of evaporites with very low permeability separates the formation from the overlying units. Simulations of human intrusion scenarios do not include a borehole pathway for fluid migration between the Bell Canyon Formation (or deeper units) and the repository. Relatively little is known about the head 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 because of brine density effects (Mercer, 1983; Beauheim, 1986; Lappin et al., 1989).

Capitan Limestone

The Capitan Limestone is not present at the WIPP but is a time-stratigraphic equivalent of the Bell Canyon and Castile Formations to the west, north, and east (Figures 5-1, 5-3). The unit is a massive limestone ranging from 76 to 230 m (250 to 750 ft) thick. Dissolution and fracturing have enhanced effective porosity, and the Capitan is a major aquifer in the region, providing the principal water supply for the city of Carlsbad. Upward flow of groundwater from the Capitan aquifer may be a factor in dissolution of overlying halite and the formation of breccia pipes. Existing breccia pipes are limited to the vicinity of the reef, as is the active subsidence in San Simon Swale (Figure 5-6) (Brinster, 1991).

Castile Formation

The Castile Formation is approximately 470 m (1540 ft) thick at the WIPP and contains anhydrites with intercalated limestones near the base and halite layers in the upper portions. Primary porosity and permeability in the Castile Formation are extremely low. However, approximately 18 wells in the region have encountered brine reservoirs in fractured anhydrite in the Castile Formation (Brinster, 1991). Hydrologic and geochemical data have been interpreted as indicating that these brine occurrences are hydraulically isolated (Lambert and Mercer, 1978; Lappin, 1988). Fluid may be derived from interstitial entrapment of connate water after deposition (Popielak et al., 1983), dehydration of the original gypsum to anhydrite (Popielak et al., 1983), or intermittent movement of meteoric waters from the Capitan aquifer into the fractured anhydrites between 360,000 and 880,000 years ago (Lambert and Carter, 1984). Pressures within these brine reservoirs are greater than those at comparable depths in other relatively permeable units in the region and range from 7 to 17.4 MPa (Lappin et al., 1989).

Pressurized brine in the Castile Formation is of concern for performance assessment because occurrences have been found at WIPP-12 within the WIPP land-withdrawal area and at ERDA-6 and other wells in the vicinity. The WIPP-12 reservoir is at a depth of 918 m (3012 ft), about 250 m (820 ft) below the repository horizon, and is estimated to contain 2.7 x 10^6 m^3 (1.7 x 10^7 barrels) of brine at a pressure of 12.7 MPa (Lappin et al., 1989). This pressure is greater than the nominal freshwater hydrostatic pressure at that depth of 9 MPa and is slightly greater than the nominal hydrostatic pressure for a column of equivalent brine at that depth of 11.1 MPa. The brine is saturated, or nearly so, with respect to halite, and has little or no potential to dissolve the overlying salt (Lappin et al., 1989). Brine could, however, reach the repository through an intrusion borehole.

Early geophysical surveys mapped a structurally disturbed zone in the vicinity of the WIPP that may correlate with fracturing or development of secondary porosity within the Castile Formation; this zone could possibly contain pressurized brine (Borns et al., 1983). Later electromagnetic surveys indicated that the brine present at WIPP-12 could underlie part of the waste panels (Earth Technology Corporation, 1988). WIPP-12 data are therefore used to develop a conceptual model of the brine reservoir for analyzing scenarios that include the penetration of pressurized brine. The numerical model for the Castile Formation brine reservoir is described in Volume 2 of this report. Data are summarized in Volume 3 of this report.

Salado Formation

The Salado Formation is about 600 m (1970 ft) thick at the WIPP and contains bedded halite rhythmically interbedded with anhydrite, polyhalite, glauberite, and some thin mudstones (Adams, 1944; Bachman, 1981; Mercer, 1983). Unlike the underlying Castile Formation, the Salado Formation overlaps the Capitan Limestone and extends eastward beyond the reef for many kilometers into west Texas (Figure 5-3). Erosion has removed the Salado Formation from the western portion of the basin (Figure 5-1).

Where the Salado Formation is intact and unaffected by dissolution, circulation of groundwater is extremely slow because primary porosity and open fractures are lacking in the plastic salt (Mercer, 1983; Brinster, 1991). The formation is not dry, however. Interstitial brine seeps into the repository at rates up to approximately 0.01 ℓ/day/m of tunnel (Bredehoeft, 1988; Nowak et al., 1988), and the Salado is assumed to be saturated

(Brinster, 1991). Porosity is estimated to be approximately 0.001 (Mercer, 1983, 1987; Powers et al., 1978a,b; Bredehoeft, 1988). Permeability of the formation is very low but measurable, with an average value of 0.05 microdarcies (5 x 10^{-20} m^2) reported by Powers et al. (1978a,b) from well tests. This value corresponds approximately to a hydraulic conductivity of approximately 5 x 10^{-13} m/s (1 x 10^{-7} ft/d). In situ testing of halite in the repository indicates lower permeabilities ranging from 1 to 100 nanodarcies (10^{-22} to 10^{-20} m^2) (Stormont et al., 1987; Beauheim et al., 1990), suggesting that the higher values may reflect properties of disturbed rock (Brinster, 1991).

Rustler-Salado Contact Zone

In the vicinity of Nash Draw, the contact between the Rustler and Salado Formations is an unstructured residuum of gypsum, clay, and sandstone created by dissolution of halite. The residuum becomes thinner to the east and intertongues with 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, indicating that some dissolution occurred before Rustler deposition (Holt and Powers, 1988).

The residuum ranges in thickness in the vicinity of the WIPP from 2.4 m (7.9 ft) in P-14 east of Nash Draw to 33 m (108 ft) in WIPP-29 within Nash Draw (Mercer, 1983). Measured hydraulic conductivity values for the residuum are highest at Nash Draw (up to 10^{-6} m/s [10^{-1} ft/d]), and three to six orders of magnitude lower to the east (Brinster, 1991). Porosity estimates range from 0.15 to 0.33 (Hale and Clebsch, 1958; Robinson and Lang, 1938; Geohydrology Associates, Inc., 1979; and Mercer, 1983).

Rustler Formation

The Rustler Formation is 95 m (312 ft) thick at the WIPP (as measured in ERDA-9) and ranges in the area from a minimum of 8.5 m (28 ft) where thinned by dissolution and erosion west of the repository to a maximum of 216 m (709 ft) to the east (Brinster, 1991). Overall, the formation is composed of about 40 percent anhydrite, 30 percent halite, 20 percent siltstone and sandstone, and 10 percent anhydritic dolomite (Lambert, 1983). On the basis of outcrops in Nash Draw west of the WIPP, the formation is divided into four formally named members and a lower unnamed member (Vine, 1963). These five units (Vine, 1963; Mercer, 1983) are, in ascending order, the unnamed lower member (oldest), the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member (youngest) (Figure 5-7).

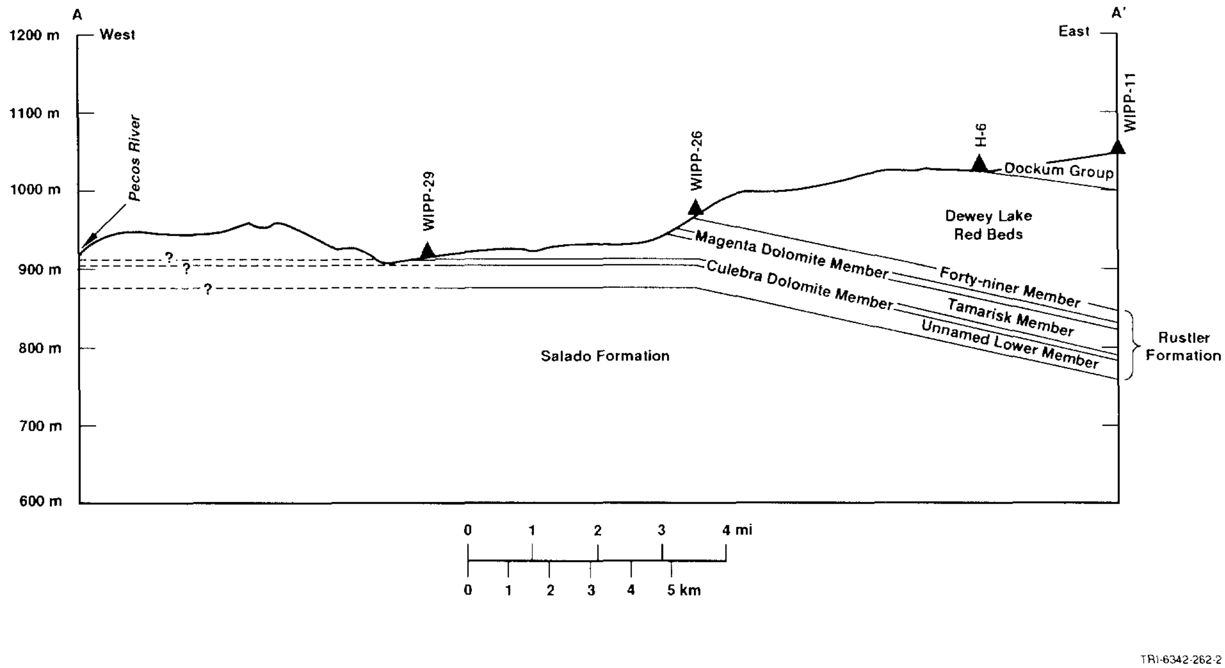

Figure 5-7. East-West Cross Section Showing Stratigraphy of the Rustler Formation and the Dewey Lake Red Beds (modified from Brinster, 1991). Note vertical exaggeration. Location of cross section is shown on Figure 5-6.

The Unnamed Lower Member

The unnamed lower member is about 36 m (118 ft) thick at the WIPP and thickens slightly to the east. The unit is composed mostly of fine-grained silty sandstones and siltstones interbedded with anhydrite (converted to gypsum at Nash Draw) west of the WIPP. Increasing amounts of halite are present to the east. Halite is present over the WIPP (Figure 5-8) but is absent north and south of the WIPP where the topographic expression of Nash Draw extends eastward. Distribution of halite within this and other members of the Rustler Formation is significant because, as is discussed in the following section, there is an apparent correlation between the absence of halite and increased transmissivity in the Culebra Dolomite Member.

The basal interval of the unnamed lower member contains siltstone and sandstone of sufficient transmissivity to allow groundwater flow. 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 from tests at H-16 that included this interval (Beauheim, 1987a). Transmissivity in the lower portion of the unnamed member is believed to increase to the west, where dissolution in the underlying Rustler-Salado contact zone has caused fracturing of the sandstone and siltstone (Beauheim and Holt, 1990).

The remainder of the unnamed lower member contains mudstones, anhydrite, and variable amounts of halite. Hydraulic conductivity of these lithologies is extremely low: tests of mudstones and claystones in the waste-handling shaft gave hydraulic conductivity values ranging from 6×10^{-15} m/s (2×10^{-9} ft/d) to 1×10^{-13} m/s (3×10^{-8} ft/d) (Saulnier and Avis, 1988; Brinster, 1991).

Culebra Dolomite Member

The Culebra Dolomite Member of the Rustler Formation is microcrystalline dolomite or dolomitic limestone with solution cavities (Vine, 1963). In the vicinity of the WIPP, it 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). Outcrops of the Culebra Dolomite occur in the southern part of Nash Draw and along the Pecos River.

The Culebra Dolomite has been identified as the most likely pathway for release of radionuclides to the accessible environment, and hydrologic research has concentrated on the unit for over a decade (Mercer and Orr, 1977; Mercer and Orr, 1979; Mercer, 1983; Mercer et al., 1987; Beauheim, 1987a,b; LaVenue et al., 1988; Davies, 1989; LaVenue et al., 1990; Cauffman et al., 1990; Brinster, 1991). Hydraulic data are available from 41 well locations in the WIPP vicinity (Cauffman et al., 1990).

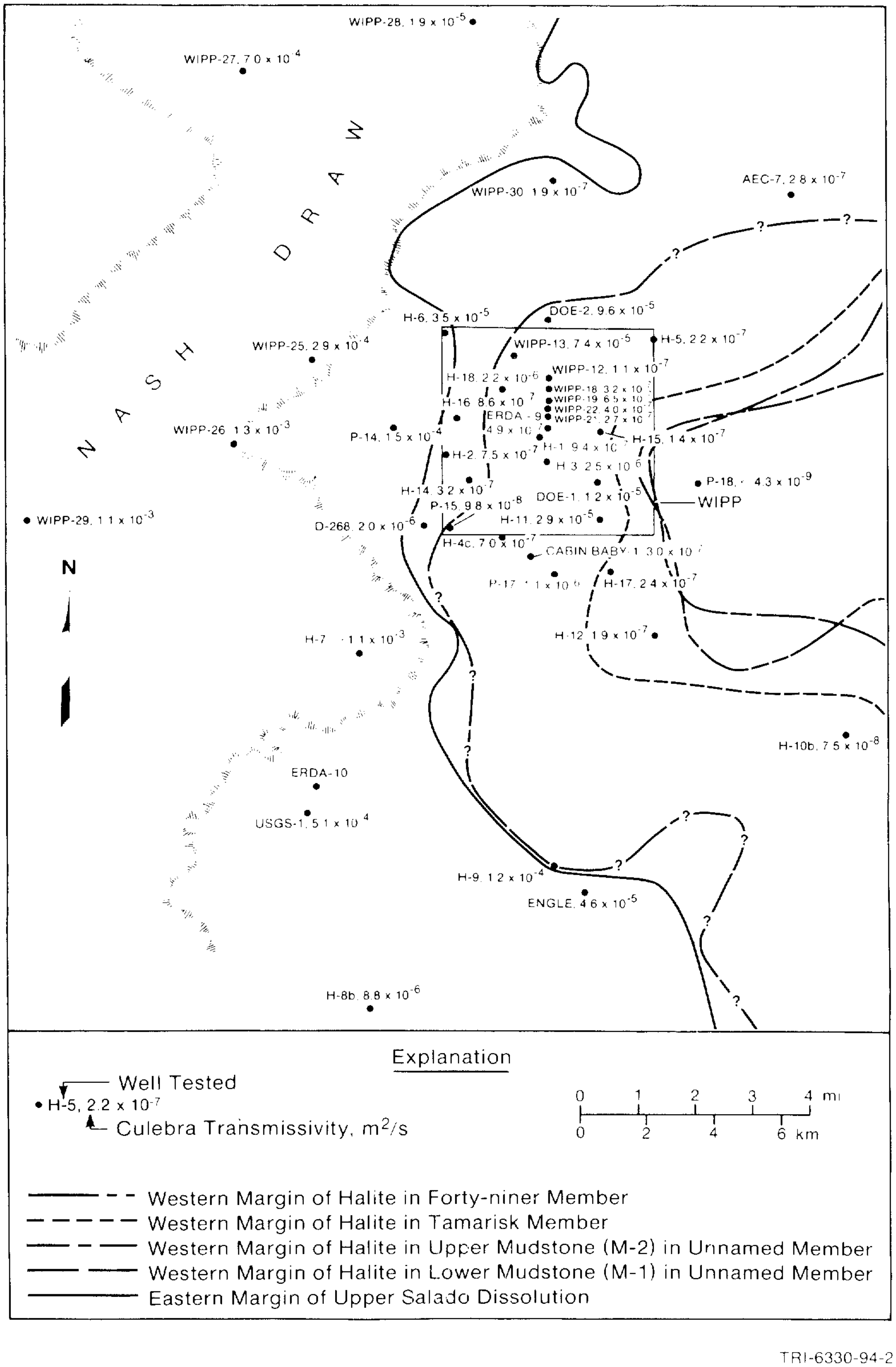

Figure 5-8. Rustler Formation Halite and Culebra Dolomite Transmissivity around the WIPP (Lappin et al., 1989).

Hydraulic conductivity of the Culebra varies six orders of magnitude from east to west in the vicinity of the WIPP (Figure 5-9), ranging from 2×10^{-10} m/s (6×10^{-5} ft/d) at P-18 east of the WIPP to 1×10^{-4} m/s (6×10^{1} ft/d) at H-7 in Nash Draw (Brinster, 1991). This variation is controlled by fracturing in the Culebra caused either by subsidence associated with post-depositional dissolution of salt in the Rustler Formation (Snyder, 1985), or by stress reduction from removal of overburden (Holt and Powers, 1988), or possibly from a combination of both processes. Present distribution of halite in the Rustler Formation correlates with hydraulic conductivity in the Culebra (Figure 5-8), suggesting a causal link between the controlling processes.

Measured matrix porosities of the Culebra Dolomite range from 0.03 to 0.30 (Lappin et al., 1989; Kelley and Saulnier, 1990). Fracture porosity values have not been measured directly, but interpreted values from tracer tests at the H-3 and H-11 hydropads are 2×10^{-3} and 1×10^{-3}, respectively (Kelley and Pickens, 1986).

Tamarisk Member

The Tamarisk Member ranges in thickness from 8 to 84 m (26 to 276 ft) in southeastern New Mexico, and is about 36 m (118 ft) thick at the WIPP. The Tamarisk consists of mostly anhydrite or gypsum interbedded with thin layers of claystone and siltstone. Near Nash Draw, dissolution has removed evaporites from the Tamarisk Member, and the Magenta and Culebra Dolomites are separated only by a few meters of residue (Brinster, 1991).

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. Permeability was too low to measure in either well within the time allowed for testing, but Beauheim (1987a) estimated the transmissivity of the claystone sequence to be one or more orders of magnitude less than that of siltstone in the unnamed lower member, which yielded values 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).

Magenta Dolomite Member

The Magenta Dolomite Member of the Rustler Formation is a fine-grained dolomite that ranges in thickness from 4 to 8 m (13 to 26 ft) and is about 6 m (19 ft) thick at the WIPP. The Magenta is saturated except near outcrops along Nash Draw, and hydraulic data are available from 14 wells. Hydraulic conductivity ranges over five orders of magnitude from 5.0×10^{-10} to 5.0×10^{-5} m/s (1×10^{-4} to 1×10^{1} ft/d).

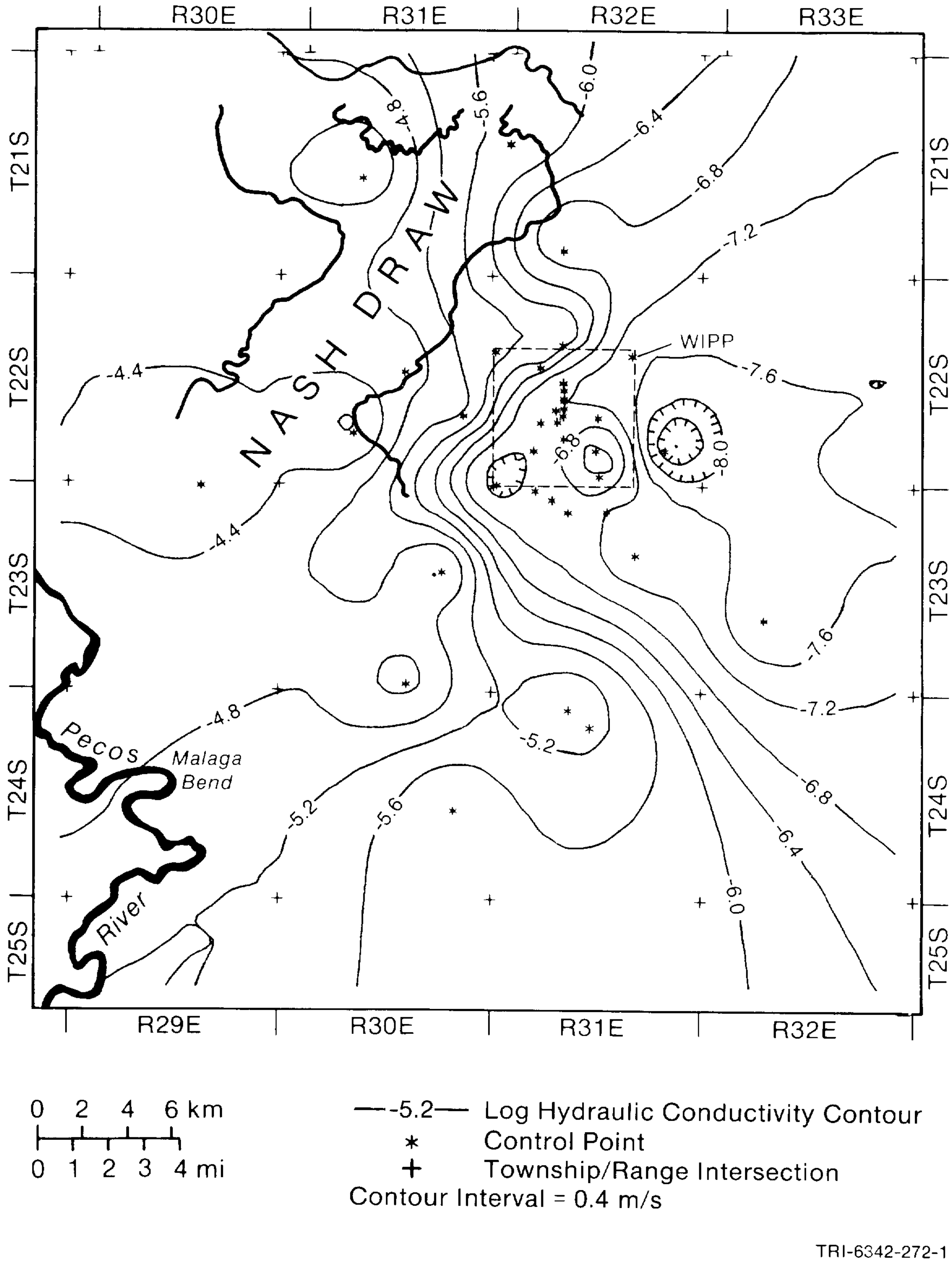

Figure 5-9. Log Hydraulic Conductivities (measured in m/s) of the Culebra Dolomite Member of the Rustler Formation (Brinster, 1991).

A contour map of log hydraulic conductivities of the Magenta Dolomite Member based on sparse data (Figure 5-10) 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 expression of Nash Draw (Brinster, 1991). Comparison of Figures 5-9 and 5-10 show that in most locations conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra.

No porosity measurements have been made on the Magenta Dolomite Member. Beauheim (1987a) assumed a representative dolomite porosity of 0.20 for interpretations of well tests.

Forty-niner Member

The uppermost member of the Rustler Formation, the Forty-niner Member, is about 20 m (66 ft) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone. Tests in H-14 and H-16 yielded hydraulic conductivities of about 5 x 10^{-9} m/s (1 x 10^{-3} ft/d) and 5 x 10^{-10} m/s (1 x 10^{-4} ft/d) respectively (Beauheim, 1987a).

Supra-Rustler Rocks

Where present, the supra-Rustler units collectively range in thickness from 4 to 536 m (13 to 1758 ft). Regionally, the supra-Rustler units thicken to the east and form a uniform wedge of overburden across the region (Brinster, 1991). Fine-grained sandstones and siltstones of the Dewey Lake Red Beds (Pierce Canyon Red Beds of Vine, 1963) conformably overlie the Rustler Formation at the WIPP and are the uppermost Permian rocks in the region. The unit is absent in Nash Draw, is 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 (Figures 5-4, 5-7). East of the WIPP, the Dewey Lake Red Beds are unconformably overlain by Mesozoic rocks of the Triassic Dockum Group. These rocks are absent above the repository and reach a thickness of over 100 m (328 ft) in western Lea County. East of the WIPP, Triassic and, in some locations, Cretaceous rocks are unconformably overlain by the Pliocene Ogallala Formation. At the WIPP, Permian strata are overlain by discontinuous sands and gravels of the Pleistocene Gatuña Formation, the informally named Pleistocene Mescalero caliche, and Holocene soils.

Drilling in the Dewey Lake Red Beds has not identified a continuous zone of saturation. Some localized zones of relatively high permeability were identified by loss of drilling fluids at DOE-2 and H-3d (Mercer, 1983; Beauheim, 1987a). Thin and apparently discontinuous saturated sands were identified in the upper Dewey Lake Red Beds at H-1, H-2, and H-3 (Mercer and

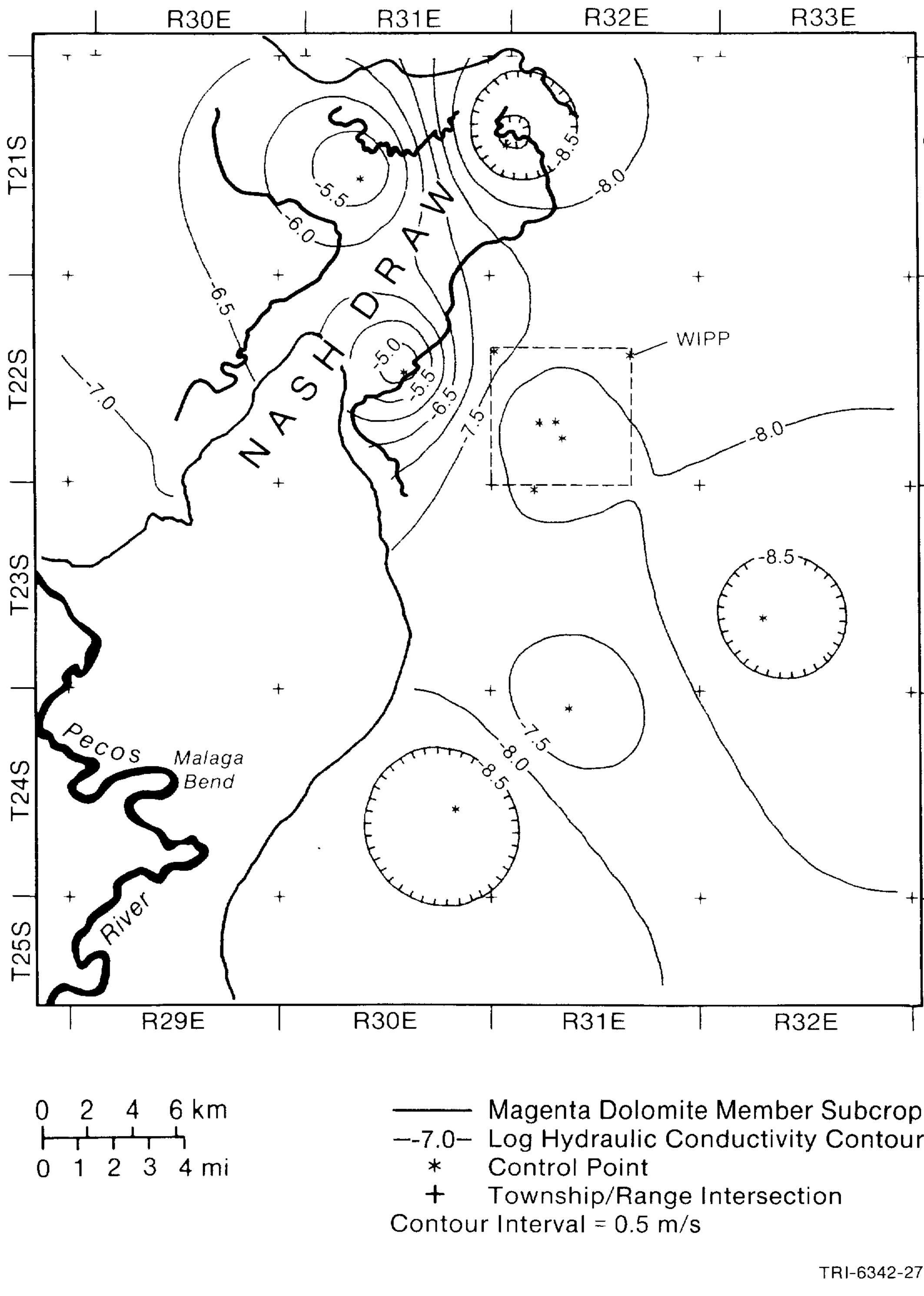

Figure 5-10. Log Hydraulic Conductivities (measured in m/s) of the Magenta Dolomite Member of the Rustler Formation (Brinster, 1991).

Orr, 1979; Mercer, 1983). Several wells operated by the J. C. Mills Ranch (James Ranch) south of the WIPP produce sufficient quantities of water from the Dewey Lake Red Beds to supply livestock (Brinster, 1991).

Hydrologic properties of supra-Rustler rocks are relatively poorly understood because of the lack of long-term hydraulic tests. Hydraulic conductivity of the Dewey Lake Red Beds, assuming saturation, is estimated to be 10^{-8} m/s (10^{-3} ft/d), corresponding to the hydraulic conductivity of fine-grained sandstone and siltstone (Mercer, 1983; Davies, 1989). Porosity is estimated to be about 0.20, which is representative of fine-grained sandstone (Brinster, 1991).

5.1.3 CLIMATE

The present climate of southeastern New Mexico is arid to semi-arid (Swift, 1991a). Annual precipitation is dominated by a late summer monsoon, when solar warming of the continent creates an atmospheric pressure gradient that draws moist air inland from the Gulf of Mexico (Cole, 1975). Winters are cool and generally dry.

Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (10.9 and 13.5 in/yr) (Hunter, 1985). At Carlsbad, 42 km (26 mi) west of the WIPP and 100 m lower in elevation, 53-year (1931-1983) annual means for precipitation and temperature are 32 cm/yr (12.6 in/yr) and 17.1°C (63°F) (University of New Mexico, 1989). Freshwater pan evaporation in the region is estimated to be 280 cm/yr (110 in/yr) (U.S. DOE, 1980a).

Short-term climatic variability can be considerable in the region. For example, the 105-year (1878 to 1982) precipitation record from Roswell, 135 km northwest of the WIPP and 60 m higher in elevation, shows an annual mean of 27 cm/yr (10.6 in/yr) with a maximum of 84 cm/yr (32.9 in/yr) and a minimum of 11 cm/yr (4.4 in/yr) (Hunter, 1985).

5.1.4 PALEOCLIMATES AND CLIMATIC VARIABILITY

Geologic data from the American Southwest show repeated alternations of wetter and drier climates throughout the Pleistocene, which correspond to global cycles of glaciation and deglaciation (Swift, 1991a). Climates in southeastern New Mexico have been coolest and wettest during glacial maxima, when the North American ice sheet reached its southern limit roughly 1200 km (750 mi) north of the WIPP. Mean annual precipitation at these extremes was approximately twice that of the present. Mean annual temperatures may have been as much as 5°C (9°F) cooler than at present. Modeling of global circulation patterns suggests these changes resulted from the disruption and southward displacement of the winter jet stream by the ice sheet, causing an increase in the frequency and intensity of winter storms throughout the Southwest (COHMAP members, 1988).

Data from plant and animal remains and paleo-lake levels permit quantitative reconstructions of precipitation in southeastern New Mexico during the advance and retreat of the last major ice sheet in North America. Figure 5-11 shows estimated mean annual precipitation for the WIPP for the last 30,000 years, based on an estimated present precipitation of 30 cm/yr (11.8 in/yr). The precipitation maximum coincides with the maximum advance of the ice sheet 22,000 to 18,000 years ago. Since the final retreat of the ice sheet approximately 10,000 years ago, conditions have been generally dry, with intermittent and relatively brief periods when precipitation may have approached glacial levels. Causes of these Holocene fluctuations are uncertain (Swift, 1991a).

Based on the past record, it is reasonable to assume that climate will change at the WIPP during the next 10,000 years, and the performance-assessment hydrologic model must allow for climatic variability. Presently available long-term climate models are incapable of resolution on the spatial scales required for numerical predictions of future climates at the WIPP (e.g., Hansen et al., 1988; Mitchell, 1989; Houghton et al., 1990), and simulations using these models are of limited value beyond several hundreds of years into the future. Direct modeling of climates during the next 10,000 years has not been attempted for WIPP performance assessment. Instead, performance-assessment modeling uses past climates to set limits for future variability (Swift, 1991a; Swift, October 10, 1991, memo in Volume 3, Appendix A). The extent to which unprecedented climatic changes caused by human-induced changes in the composition of the Earth's atmosphere may invalidate this assumption is uncertain. Presently available models of climatic response to an enhanced greenhouse effect (e.g., Mitchell, 1989; Houghton et al., 1990) do not predict changes of a larger magnitude than those of the Pleistocene (although predicted rates of change are far greater), suggesting the choice of a Pleistocene analog for future climatic extremes will remain appropriate. Future WIPP performance assessments will re-examine the assumption, taking into account the result of ongoing research in the fields of climate change.

Glacial periodicities have been stable for the last 800,000 years, with major peaks occurring at intervals of 19,000, 23,000, 41,000 and 100,000 years, corresponding to variations in the Earth's orbit (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984; Imbrie, 1985). Barring anthropogenic changes in the Earth's climate, relatively simple modeling of the nonlinear climatic response to astronomically controlled changes in the amount of solar energy reaching the Earth suggests that the next glacial maximum will occur in approximately 60,000 years (Imbrie and Imbrie, 1980). Regardless of

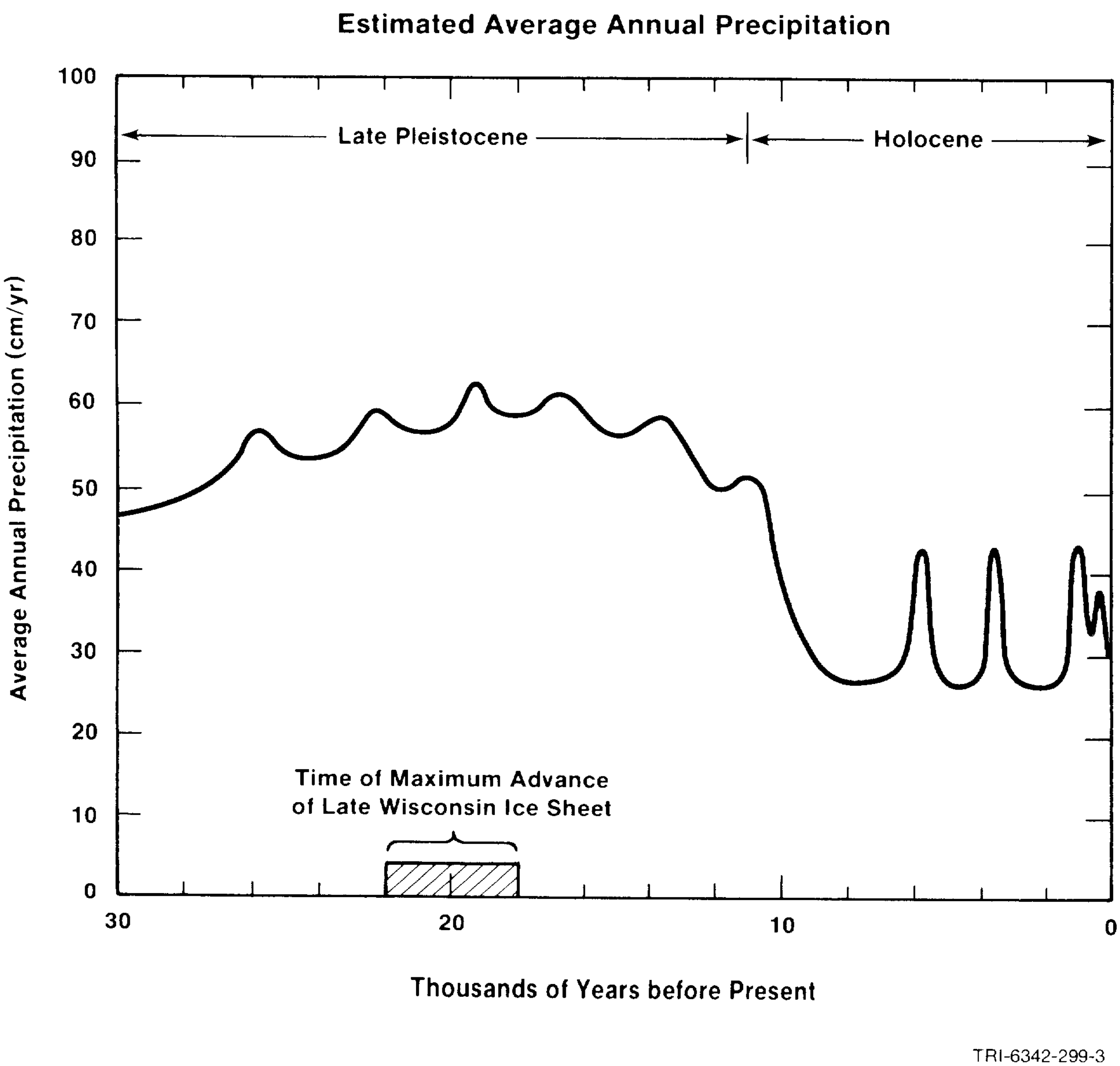

Figure 5-11. Estimated Mean Annual Precipitation at the WIPP during the Late Pleistocene and Holocene (modified from Swift, 1991a).

anthropogenic effects, short-term climatic fluctuations comparable to those of the last 10,000 years are probable during the next 10,000 years and must be included in performance-assessment modeling.

Climatic variability will be incorporated into the modeling system conceptually by varying groundwater flow into the Culebra Dolomite Member of the Rustler Formation as a scaled function of precipitation (Swift, October 10, 1991, memo in Volume 3, Appendix A). Short-term variability in precipitation is approximated with a periodic function that generates peaks of twice present precipitation every 2000 years and a future climate that is, on the average, wetter than that of the present one half of the time. Long-term, glacial increase in precipitation is approximated with a periodic function that reaches a maximum of twice present precipitation in 60,000 years. For this performance assessment, climatic variability has been included in the consequence analysis by varying boundary conditions of the Culebra groundwater-flow model as a scaled function of future precipitation. As discussed further in Section 5.1.9-Culebra Dolomite Groundwater Flow and Transport in this chapter and in Volume 2, potentiometric heads along a portion of the northern boundaries of the regional model domain were varied between present elevation and the ground surface, reaching maximum elevations at times of maximum precipitation.

5.1.5 SURFACE WATER

The Pecos River, the principal surface-water feature in southeastern New Mexico, flows southeastward in Eddy County approximately parallel to the axis of the Delaware Basin (Figure 5-1) and drains 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). At its closest point the Pecos River is about 20 km (12 mi) southwest of the WIPP (Brinster, 1991).

Very little, if any, of the surface water from Nash Draw reaches the Pecos River (Robinson and Lang, 1938; Lambert, 1983). Several shallow, saline lakes in Nash Draw cover an area of about 16 km^2 (6 mi^2) southwest of the WIPP (Figure 5-6) and collect precipitation, surface drainage, and groundwater discharge from springs and seeps. The largest lake, Laguna Grande de la Sal, has existed throughout historic time. 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 has also enlarged Laguna Grande de la Sal.

5.1.6 THE WATER TABLE

No detailed maps of the water table are available for the vicinity of the WIPP. Outside of the immediate vicinity of the Pecos River, where water is pumped for irrigation from an unconfined aquifer in the alluvium, near-surface rocks are either unsaturated or of low permeability and do not produce water in wells. Tests of the lower Dewey Lake Red Beds in H-14 that were intended to provide information about the location of the water table proved inconclusive because of low transmissivities (Beauheim, 1987a). Livestock wells completed south of the WIPP in the Dewey Lake Red Beds at the J. C. Mills Ranch (James Ranch) may produce from perched aquifers (Mercer, 1983; Lappin et al., 1989), or they may produce from transmissive zones in a continuously saturated zone that is elsewhere unproductive because of low transmissivities.

Regionally, water-table conditions can be inferred for the more permeable units where they are close to the surface and saturated. The Culebra Dolomite may be under water-table conditions in and near Nash Draw and near regions of Rustler Formation outcrop in Bear Grass Draw and Clayton Basin north of the WIPP (Figure 1-6). The Magenta Dolomite is unsaturated and presumably above the water table at WIPP-28 and H-7 near Nash Draw. Water-table conditions exist in the Rustler-Salado contact zone near where it discharges into the Pecos River at Malaga Bend (Brinster, 1991).

5.1.7 REGIONAL WATER BALANCE

Hunter (1985) examined the overall water budget of approximately 5180 km^2 (2000 mi^2) surrounding the WIPP. Water inflow to the area comes from precipitation, surface-water flow in the Pecos River, groundwater flow across the boundaries of the region, and water imported to the region for human use. Outflow from the water-budget model occurs as stream-water flow in the Pecos River, groundwater flow, and evapotranspiration. Volumes of water gained by precipitation and lost by evapotranspiration are more than one order of magnitude larger than volumes gained or lost by other means.

Uncertainties about precipitation, evapotranspiration, and water storage within the system limit the usefulness of estimates of groundwater recharge based on water budget analyses. Regionally, Hunter (1985) concluded that approximately 96 percent of precipitation was lost directly to evapotranspiration, without entering the surface or groundwater flow systems. Within the 1000 km^2 immediately around the WIPP, where no surface runoff occurs and all precipitation not lost to evapotranspiration must recharge groundwater, a separate analysis suggested evapotranspiration may be as high as 98 to 99.5 percent (Hunter, 1985). Direct measurements of infiltration rates are not available from the WIPP vicinity.

5.1.8 GROUNDWATER FLOW ABOVE THE SALADO FORMATION

Well tests indicate that the three most permeable units in the vicinity of the WIPP above the Salado Formation are the Culebra Dolomite and Magenta Dolomite Members of the Rustler Formation and the residuum at the Rustler-Salado contact zone. The vertical permeabilities of the strata separating these units are not known, but lithologies and the potentiometric and geochemical data summarized below suggest that for most of the region, vertical flow between the units is very slow. Although preliminary hydrologic modeling indicates that some component of vertical flow between units can be compatible with observed conditions (Haug et al., 1987; Davies, 1989), the units are assumed to be perfectly confined for the 1991 performance-assessment calculations.

Potentiometric Surfaces

Mercer (1983) and Brinster (1991) have constructed potentiometric-surface maps for the Rustler-Salado residuum, the Culebra Dolomite, and the Magenta Dolomite. Brinster's (1991) maps are reproduced here (Figures 5-12, 5-13, and 5-14). These maps show the level to which fresh water would rise in a well open to each unit. Contours are based on measured heads (water elevations in wells) that have been adjusted to freshwater-equivalent heads (the level to which fresh water would rise in the same well). Maps for the Culebra and the Magenta Dolomites are based on data from 31 and 16 wells, respectively. The map for the Rustler-Salado residuum includes data from 14 wells and water elevations in the Pecos River, reflecting an assumption that water-table conditions exist in the unit near the river.

Because the data used to construct the potentiometric maps are sparse and unevenly distributed, interpretations must be made with caution. For example, the "bullseye" patterns visible in all three maps are controlled by single data points, and would probably disappear from the maps if sufficient data were available. Contours are most reliable where data are closely spaced, particularly in the immediate vicinity of the WIPP, and are least reliable where they have been extrapolated into areas of no data, such as the southeast portion of the mapped area. With these caveats noted, however, the potentiometric maps can be useful in drawing conclusions about flow both within and between the three units.

Flow of a constant-density liquid within an isotropic medium would be perpendicular to the potentiometric contours. Near the WIPP, localized regions have been identified where variations in brine density result in non-uniform gravitational driving forces and anomalous flow directions (Davies, 1989), and the effects of anisotropy on flow patterns are not fully

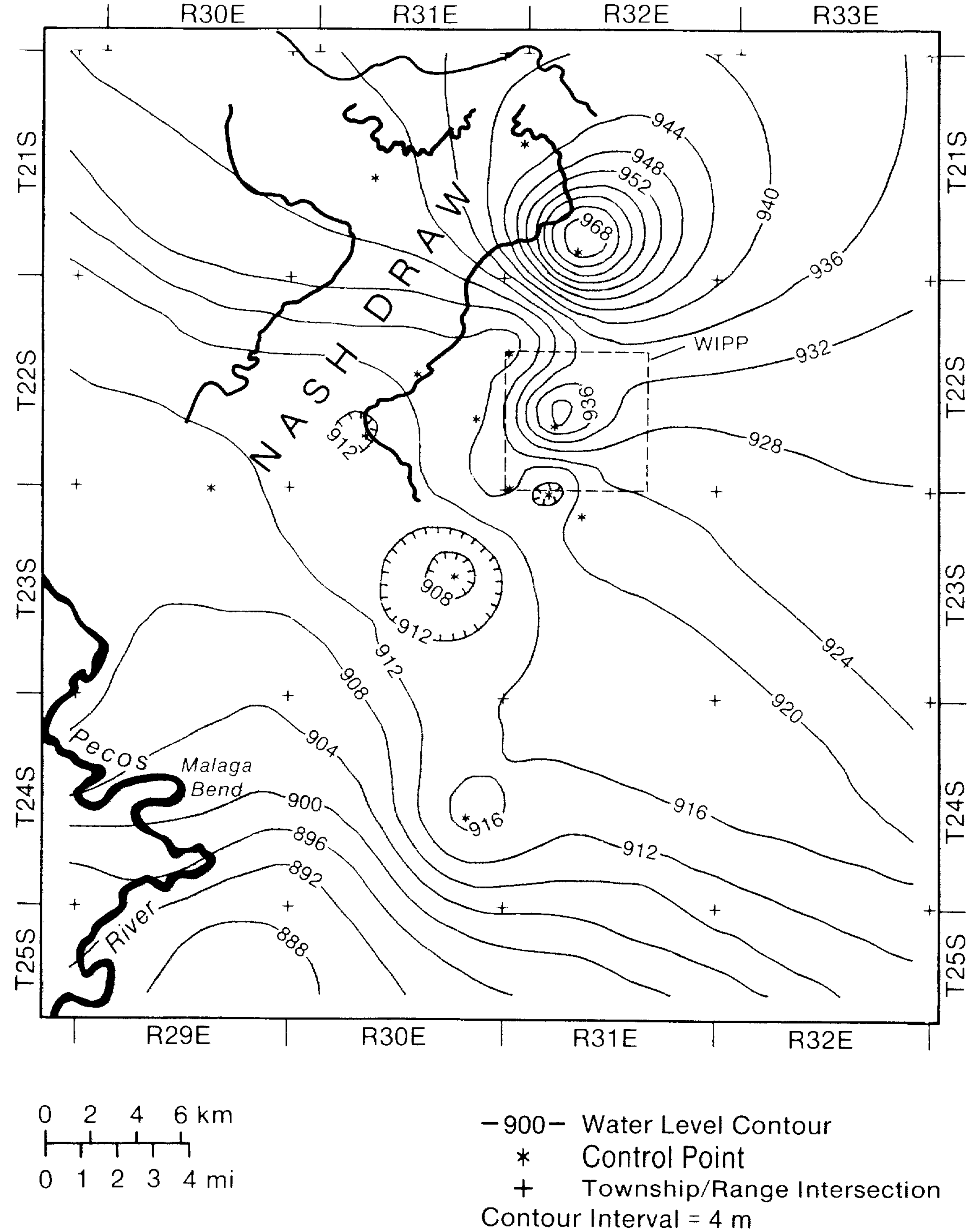

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Figure 5-12. Adjusted Potentiometric Surface of the Rustler-Salado Residuum in the WIPP Vicinity (Brinster, 1991). Contours based on data from indicated wells and the elevation of the Pecos River.

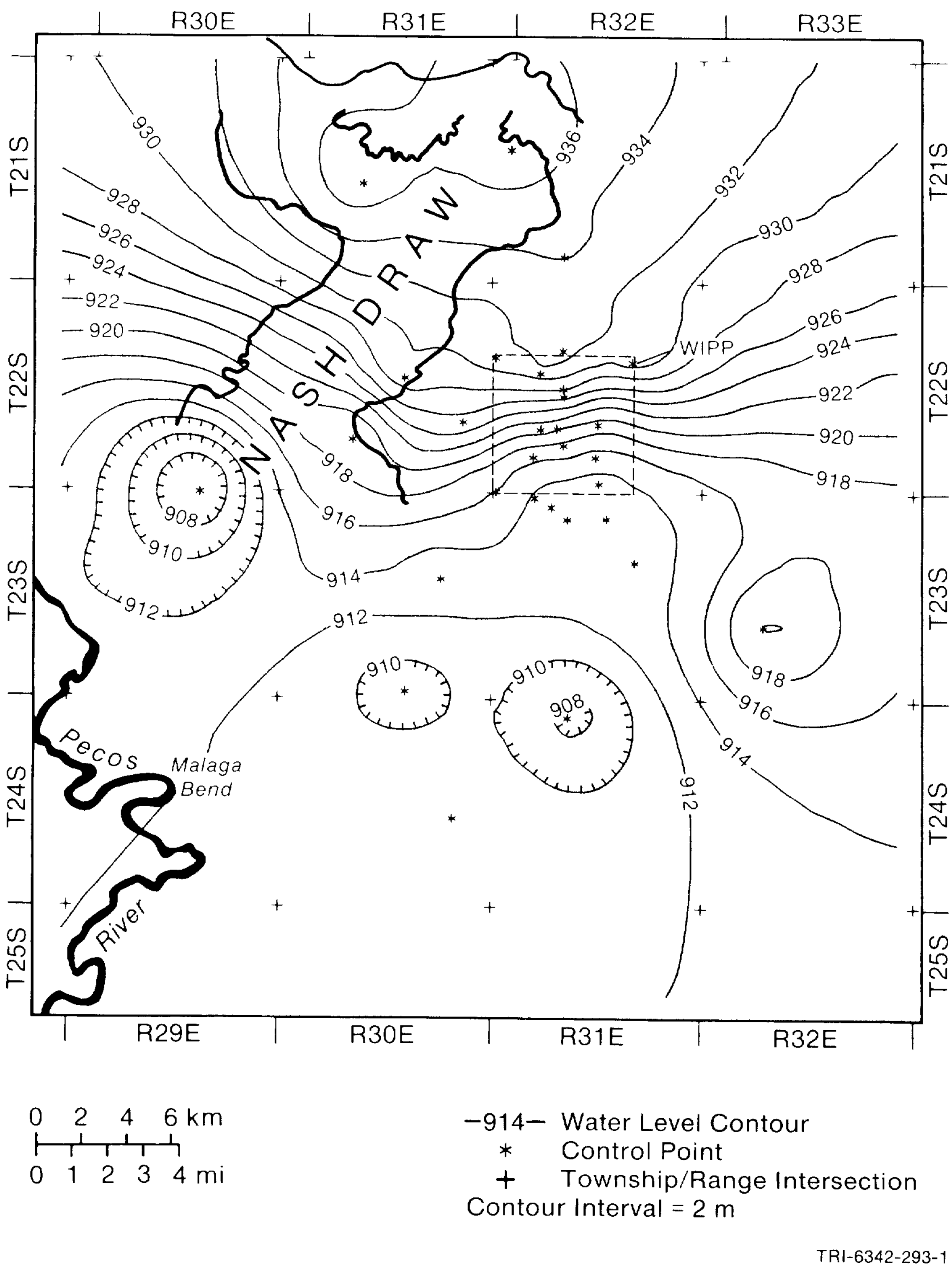

Figure 5-13. Adjusted Potentiometric Surface of the Culebra Dolomite Member of the Rustler Formation in the WIPP Vicinity (Brinster, 1991). Contours based on data from indicated wells.

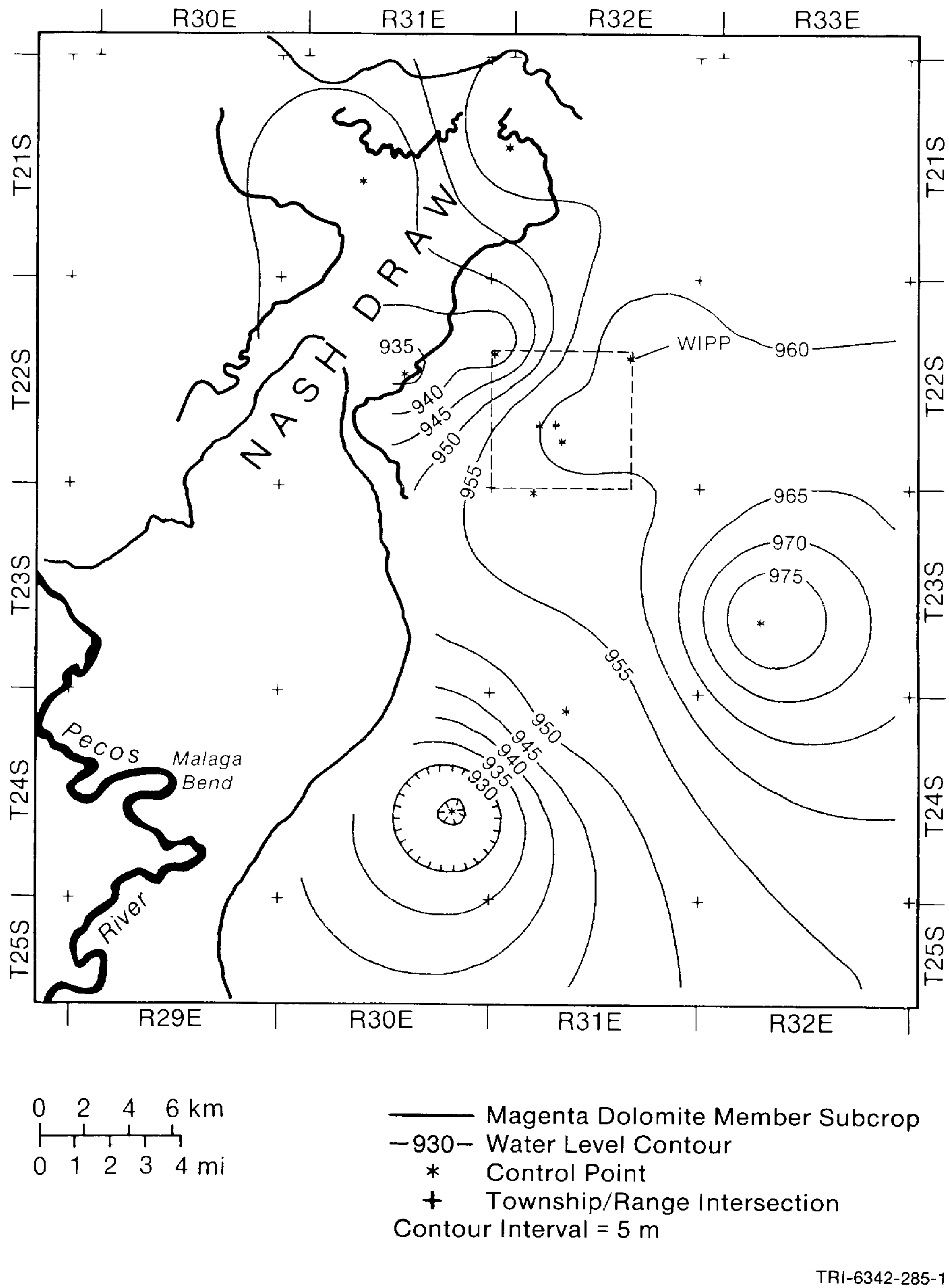

Figure 5-14. Adjusted Potentiometric Surface of the Magenta Dolomite Member of the Rustler Formation in the WIPP Vicinity (Brinster, 1991). Contours based on data from indicated wells.

understood. In general, however, flow in the Rustler-Salado residuum is from northeast to southwest. Flow in the Culebra is from north to south, and flow in the Magenta is from east to west in that portion of the map where data are sufficient to permit interpretation. Differences in flow directions may reflect long-term transient conditions (see "Recharge and Discharge" in Section 5.1.8-Confined Hydrostatigraphic Units) and indicate low permeability of the strata separating the three units: if the three functioned as a single aquifer, potentiometric maps would be similar.

Flow between units is also a function of hydraulic gradient and can be interpreted qualitatively from the potentiometric maps. Like lateral flow within units, vertical flow between units is from higher potentiometric levels to lower levels. Differences between the elevations of the potentiometric surfaces reflect low permeabilities of the intervening strata and slow rates of vertical leakage relative to rates of flow within the aquifers. Brinster (1991), Beauheim (1987a), and Holt et al. (in prep., summarized by Brinster, 1991) present analyses of vertical hydraulic gradients on a well-by-well basis. These analyses suggest that, if flow occurs, the direction of flow between the Magenta and the Culebra is downward throughout the WIPP area. Directly above the repository, flow may be upward from the Rustler-Salado residuum to the Culebra Dolomite. Elsewhere in the region, both upward and downward flow directions exist between the two units.

Groundwater Geochemistry

Major solute geochemical data are available for groundwater from the Rustler-Salado contact zone from 20 wells, from the Culebra Dolomite from 32 wells, and from the Magenta Dolomite from 12 wells (Siegel et al., 1991). Groundwater quality in all three units is poor, with total dissolved solids (TDS) exceeding 10,000 mg/ℓ (the concentration specified for regulation by the Individual Protection Requirements of the Standard) in most locations.

Waters from the Rustler-Salado residuum have the highest TDS concentrations of any groundwaters in the WIPP area. The lowest concentration reported from the unit is 70,000 mg/ℓ from H-7c southwest of the WIPP, and the highest is 410,000 mg/ℓ from H-5 at the northeast corner of the land-withdrawal area (Siegel et al., 1991).

Waters from the Magenta Dolomite are the least saline of those in the confined units. Within the land-withdrawal area, TDS concentrations range from approximately 4000 to 25,000 mg/ℓ. Higher values are reported from H-10 southeast of the WIPP, where the sample is of uncertain quality, and from WIPP 27 in Nash Draw, where groundwater chemistry has been altered by dumping of effluent from potash mines (Siegel et al., 1991).

Groundwater chemistry is variable in the Culebra Dolomite. A maximum TDS concentration of 240,000 mg/ℓ is reported from H-15 immediately east of the WIPP, and a minimum value of 2500 mg/ℓ is reported from H-8, 14 km (9 mi) southwest of the repository. Three other wells (H-7, H-9, and the Engle well), all south of the WIPP, also contain water with less than 10,000 mg/ℓ TDS. In a single test in February 1977, H-2 immediately west of the repository yielded water with a TDS concentration of 8900 mg/ℓ. Three subsequent tests over the following decade yielded TDS levels of 12,500, 13,000, and 11,000 mg/ℓ (Lappin et al., 1989).

Relative concentrations of major ions vary spatially within the Culebra Dolomite. Siegel et al. (1991) recognized four zones containing distinct hydrochemical facies (Figure 5-15) and related water chemistry to the distribution of halite in the Rustler Formation. 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 unnamed lower 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, extending 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 unnamed lower 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 that reflect contamination by effluent from potash mines.

Distribution of the hydrochemical facies may not be consistent with the inferred 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 from the surface could account for the characteristics of Zone B. As discussed in more detail below ("Recharge and Discharge" section), the inconsistency between chemical and potentiometric data could also result from a change in location and amount of recharge since the wetter climate of the last glacial maximum. Present flow in the Culebra could be transient, reflecting gradual drainage of a groundwater reservoir filled during the Pleistocene. Regional hydrochemical facies may not have equilibrated with

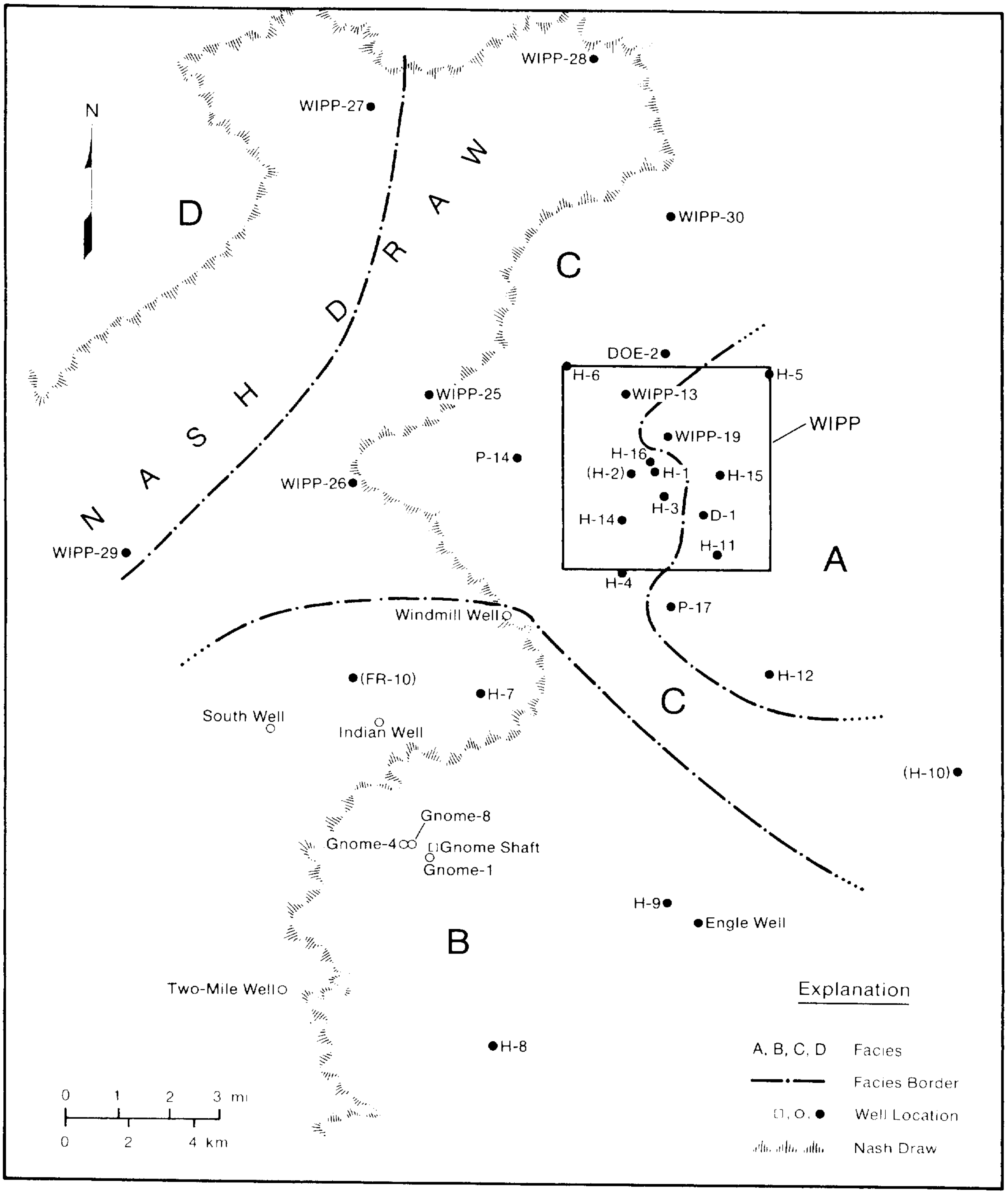

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Figure 5-15. Hydrochemical Facies in the Culebra Dolomite Member of the Rustler Formation (Siegel et al., 1991).

the modern flow regime and instead may reflect geographic distribution of halite during a past flow regime (Siegel and Lambert, 1991).

Recharge and Discharge

The only documented points of naturally occurring groundwater discharge in the vicinity of the WIPP are the saline lakes in Nash Draw and the Pecos River, primarily near Malaga Bend (Hunter, 1985; Brinster, 1991). Discharge into the lakes from Surprise Spring was measured at a rate of less than 0.01 m^3/s (0.35 ft^3/s) in 1942 (Hunter, 1985). Estimated total groundwater discharge into the lakes is 0.67 m^3/s (24 ft^3/s) (Hunter, 1985). Based on chemical and potentiometric data, Mercer (1983) concluded that discharge from the spring was from the Tamarisk Member of the Rustler Formation, and that the lakes were hydraulically isolated from the Culebra Dolomite and lower units. Lambert and Harvey's (1987) analysis of stable isotopes in water from Surprise Spring supports this conclusion: the isotopic compositions indicate that Surprise Spring and Laguna Grande de la Sal are not discharge points for the Culebra Dolomite.

Groundwater discharge into the Pecos River is many orders of magnitude larger than discharge into the saline lakes. Based on 1980 stream-flow gage data, Hunter (1985) estimated that groundwater discharge into the Pecos River between Avalon Dam north of Carlsbad and a point south of Malaga Bend was no more than approximately 9.2×10^{14} m^3/s (23,600 ac-ft/yr). Most of this gain in stream flow occurs near Malaga Bend and is the result of groundwater discharge from the residuum at the Rustler-Salado contact (Hale et al., 1954; Kunkler, 1980; Hunter, 1985; Brinster, 1991).

The only documented point of groundwater recharge is also near Malaga Bend, where an almost immediate water-level rise has been reported in a Rustler-Salado residuum well following a heavy rainstorm (Hale et al., 1954). This location is hydraulically down-gradient from the repository, and recharge here has little relevance to flow near the WIPP. Examination of the potentiometric-surface map for the Rustler-Salado residuum (Figure 5-12) indicates that some inflow must occur north of the WIPP, where freshwater-equivalent heads are highest. Additional inflow to the residuum may occur as leakage from overlying units, particularly where the units are close to the surface and under water-table conditions. Brinster (1991) proposed that inflow to the residuum (and other water-bearing units in the Rustler Formation) could also come from below, upward through breccia pipes from the Capitan aquifer north and east of the repository.

There is no direct evidence for the location of either recharge to or discharge from the Culebra Dolomite. The potentiometric-surface map (Figure 5-13) indicates recharge from the north and discharge to the south.

Mercer (1983) suggested that recharge from the surface probably occurred 15 to 30 km (9 to 19 mi) north of the WIPP at Clayton Basin and Bear Grass Draw, where the Rustler Formation crops out. Small amounts of inflow may also occur as leakage from overlying units throughout the region.

The potentiometric-surface map (Figure 5-13) indicates that flow in the Culebra Dolomite is toward the south. Some of this southerly flow may enter the Rustler-Salado residuum under water-table conditions near Malaga Bend and ultimately discharge into the Pecos River. Additional flow may discharge directly into the Pecos River or into alluvium in the Balmorhea-Loving Trough to the south (Figure 5-6) (Brinster, 1991).

Recharge to the Magenta Dolomite may also occur north of the WIPP in Bear Grass Draw and Clayton Basin (Mercer, 1983). The potentiometric-surface map indicates that discharge is toward the west in the vicinity of the WIPP, probably into the Tamarisk Member and the Culebra Dolomite near Nash Draw. Some discharge from the Magenta Dolomite may ultimately reach the saline lakes in Nash Draw. Additional discharge probably reaches the Pecos River at Malaga Bend or alluvium in the Balmorhea-Loving Trough (Brinster, 1991).

Isotopic data from groundwater samples suggest that groundwater travel time from the surface to the Dewey Lake Red Beds and the Rustler Formation is long and rates of flow are extremely slow. Low tritium levels in all WIPP-area samples indicate minimal contributions from the atmosphere since 1950 (Lambert and Harvey, 1987). Four modeled radiocarbon ages from Rustler Formation and Dewey Lake Red Beds groundwater are between 12,000 and 16,000 years. Observed uranium isotope activity ratios require a conservative minimum residence time in the Culebra Dolomite of several thousands of years and more probably reflect minimum ages of 10,000 to 30,000 years (Lambert and Carter, 1987). Stable-isotope data are more ambiguous: Lambert and Harvey (1987) concluded that compositions are distinct from modern surface values and that the contribution of modern recharge to the system is slight, whereas Chapman (1986, 1988) concluded that available stable-isotope data do not permit interpretations of groundwater age. Additional stable-isotope research is in progress and may resolve some uncertainty about groundwater age.

Potentiometric data from four wells support the conclusion that little infiltration from the surface reaches the water-bearing units of the Rustler Formation. Hydraulic head data are available for a claystone in the Forty-niner Member from DOE-2, H-3, H-4, H-5, and H-6. Comparison of these heads to Magenta heads in surrounding wells shows that flow between the units at all four wells may be upward (Holt et al., in prep., summarized by Brinster, 1991; Beauheim, 1987a). This observation offers no insight into the possibility of infiltration reaching the Forty-niner Member, but it rules out the possibility of infiltration reaching the Magenta Dolomite or any deeper units at these locations.

Location and amount of groundwater recharge and discharge in the area may have been substantially different during wetter climates of the Pleistocene. Gypsiferous spring deposits on the east side of Nash Draw are of late Pleistocene age and reflect discharge from an active water table in the Rustler Formation (Bachman, 1981; 1987; Davies, 1989; Brinster, 1991). Coarse sands and gravels in the late Pleistocene Gatuña Formation indicate deposition in high-energy, through-going drainage systems unlike those presently found in the Nash Draw area (Bachman, 1987). Citing isotopic evidence for a Pleistocene age for Rustler Formation groundwater, Lambert and Carter (1987) and Lambert (1991) have speculated that during the late Pleistocene, Nash Draw may have been a principal recharge area, and flow in the vicinity of the WIPP may have been eastward. In this interpretation, there is essentially no recharge at the present, and the modern groundwater-flow fields reflect the gradual draining of the strata. Preliminary modeling of long-term transient flow in a two-dimensional, east-west cross section indicates that, although the concept remains unproven, it is not incompatible with observed hydraulic properties (Davies, 1989). As the performance-assessment groundwater-flow model (see following section) is further developed and refined, the potential significance of uncertainty in the location and amount of future recharge will be re-evaluated.

5.1.9 THE CULEBRA DOLOMITE GROUNDWATER FLOW AND TRANSPORT MODELS

Performance-assessment modeling at present simulates groundwater flow and radionuclide transport only in the Culebra Dolomite Member of the Rustler Formation, which has been identified as the most transmissive saturated unit overlying the repository. For the 1991 calculations, the unit is modeled as a perfectly confined two-dimensional aquifer. The implications of this simplifying assumption are not fully understood, and the conceptual model for groundwater flow will be re-examined in subsequent performance assessments when the computational tools for three-dimensional flow models become available.

Details of the programs used to simulate flow and transport in the Culebra Dolomite are described in Volume 2 of this report. Darcy flow is calculated for a single phase (liquid) using the SECO_2D program (Volume 2, Chapter 6 of this report). The program solves a transient equation for groundwater flow and includes capabilities for regional and local area grid solutions, generalized boundary conditions, flexible specification of initial conditions, parameterized climate variability, particle tracking, and confined or unconfined storage coefficients. The program also has automated specification of grid spacing and times steps, options for cell-centered or node-centered grids, and efficient multigrid solvers.

Radionuclide transport is assumed to occur in a dual-porosity (fractures and matrix) medium and is calculated using the STAFF2D program (Huyakorn et al., 1989). STAFF2D is a two-dimensional finite-element program designed to simulate groundwater flow and solute transport in fractured or granular aquifers including physical and chemical retardation. The program takes into account fluid interactions between the fractures and porous matrix blocks, advective-dispersive transport in the fractures, and diffusion in the porous matrix blocks and fracture skin. The program also simulates radioactive decay during transport.

Regional and Local Model Domains for Groundwater Flow

Regional and local domains for the groundwater-flow model are shown in Figure 5-16. Flow that directly affects regulatory compliance occurs within the approximately 5-km-by-7-km local domain, which uses 125-m-by-125-m grid blocks and has relatively good control from well data. Boundary conditions for the local domain are provided by simulations within the regional domain, which uses a relatively coarser grid and has sparser well control. Initial boundary conditions for the 25-km-by-30-km regional grid are selected to be compatible with regional hydrogeologic constraints, and are adjusted during model calibration.

Uncertainty in the Transmissivity Field

Transmissivity values for the Culebra Dolomite are known from 41 well locations in the vicinity of the WIPP. These values have been used to construct and calibrate a transmissivity field that is compatible with observed head data (LaVenue et al., 1990). No calibrated field can provide a unique characterization of spatial variability in transmissivity between well locations, however, and performance-assessment calculations must take this uncertainty into account by sampling a range of transmissivity values. The 1990 calculations used a zonal approach in which the model domain was divided into coarse geographic zones, each of which was assigned a range and distribution of hydraulic conductivity values derived directly from the transmissivity values from wells. Sampling on transmissivity within the zones allowed for a probabilistic assessment of groundwater flow, but the resulting fields were not conditioned on the available head data, and transmissivity values were not correlated between zones.

In March 1991, the WIPP performance-assessment team convened a group of geostatistics consultants to advise on suitable methods for including

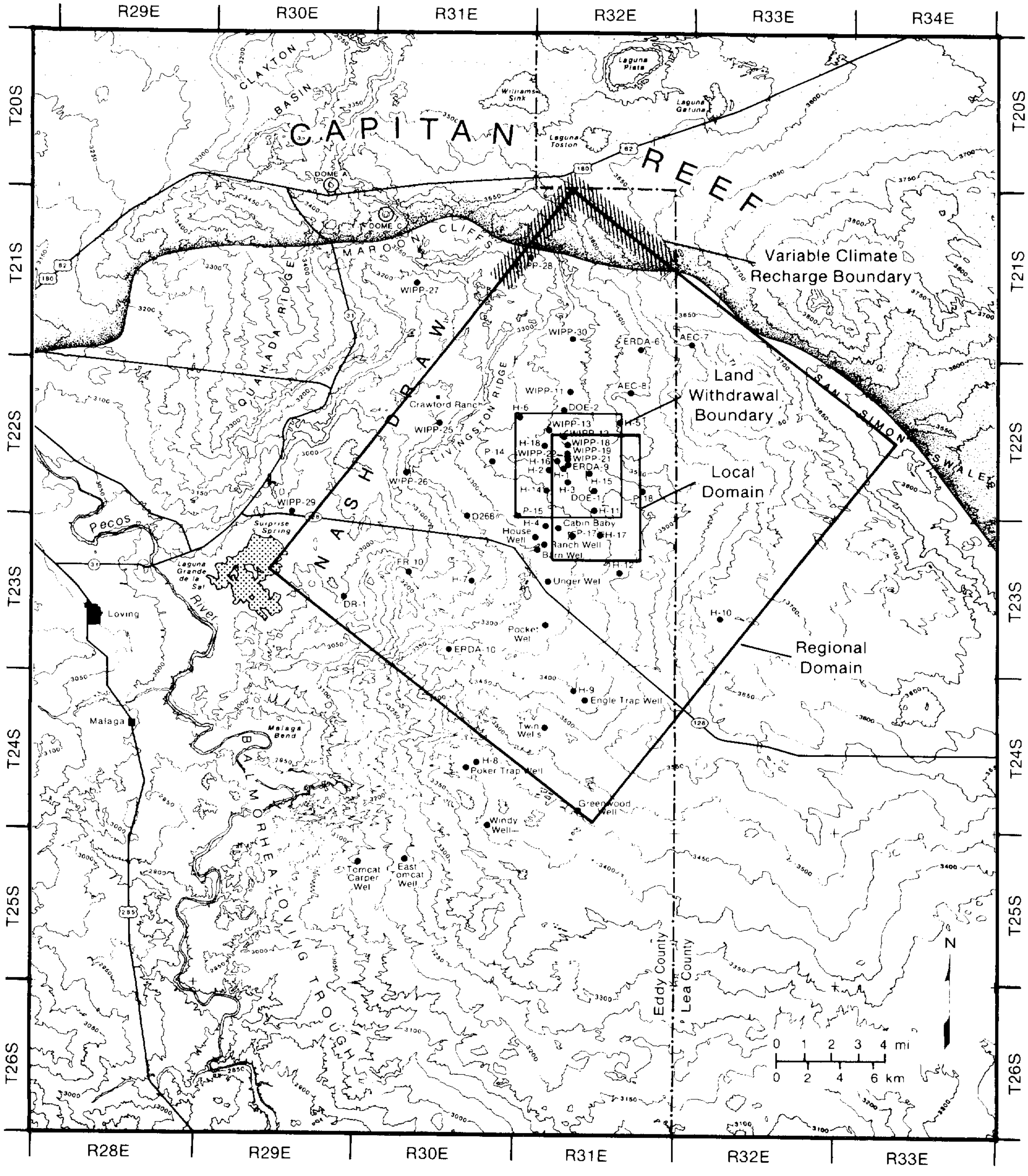


Figure 5-16. Regional and Local Domains Used for Simulations of Groundwater Flow and Transport. The regional domain is used for SECO_2D simulations of groundwater flow. The local domain is used for SECO_2D flow simulations and STAFF2D transport simulations.

uncertainty in groundwater flow and transport models. The group was requested to make suggestions that could be implemented by June 1991 to be used in the 1991 calculations. The group was also asked to suggest techniques that could be implemented in 1992 or later and to make recommendations about possible future data acquisition.

With regard to displaying the uncertainty in the transmissivity field, the consultant group proposed that a set (e.g., 100 or more) of correlated and conditioned random transmissivity fields should be generated separately, and the probabilistic sampling methodology should randomly select one of these fields for each Monte Carlo performance-assessment run. Each of these random fields should have an equal probability, or alternatively, a probability based on a "goodness-of-fit" criterion between observed and calculated heads and an assumed distribution of measurement uncertainty. For sensitivity analysis purposes, these random fields should be ordered with respect to a given criterion, such as travel time to the accessible environment.

As described in more detail in Volume 2 of this report, for the 1991 calculations 60 regional transmissivity fields have been calibrated to observed head data by adjusting boundary conditions. The multiple fields were simulated based on local estimates of transmissivity and the generalized covariance derived from them and on the pilot points used by LaVenue et al. (1990). Each simulated field was checked for consistency with pre-excavation equilibrium pressures by identifying fixed boundary pressures that minimize the squared deviation of model pressures from estimated equilibrium pressures. Boundary pressures were constrained by a prior estimate obtained through kriging the equilibrium freshwater heads. Only those fields that produced a minimum squared error of model pressures less than 2 (within the 95 percent confidence level on observed heads) were retained as plausible. These fields were assigned equal probability for Latin hypercube sampling. To facilitate sensitivity studies, the retained fields were ordered on travel time from the center of the waste panel region to the boundary of the accessible environment.

Modeling the Effects of Climatic Change

The effects of climatic change are examined in the 1991 preliminary performance assessment by varying boundary conditions for the regional model domain (see Section 5.1.4-Paleoclimates and Climatic Variability above and Swift, October 10, 1991, memo in Volume 3, Appendix A for additional information about climatic variability). As discussed further in Volume 2 of this report, groundwater flow into the model, which is assumed to be an uncertain function of mean annual precipitation, was controlled in the 1991 performance-assessment calculations by prescribing potentiometric heads along approximately 15 km of the northern boundaries of the regional model domain

(Figure 5-16). Heads within the "recharge strip" were varied between their present estimated elevations and a maximum elevation of the ground surface, using a sampled scaling factor uniformly distributed between zero and one. Maximum head values, and therefore maximum groundwater flows into the model, occurred at precipitation maximums calculated using the precipitation function described in Chapter 4 of this volume and in the October 10, 1991 memo by Swift in Volume 3, Appendix A. For those vectors with a large (close to one) scaling factor, the maximum heads were close to the ground surface. For vectors with a small (close to zero) scaling factor, the effect of climate variability was muted, and heads varied little from their present values.

This representation of variable recharge to the Culebra reflects a single, preliminary conceptual model for the effects of climatic change. Alternative conceptual models and refinement of this model will be examined in future analyses. For the 1991 preliminary comparison, variable heads were prescribed only along the northern edge of the model because, as discussed previously in "Recharge and Discharge" in Section 5.1.8-Confined Hydrostratigraphic Units in this chapter, potentiometric maps indicate north-to-south flow in the Culebra and probable recharge north of the modeled area. Maximum head elevations were limited to the ground surface because geologic evidence does not indicate the presence of widespread surface water in the region during the late Pleistocene. The sampled scaling factor reflects uncertainty in the extent to which increases in precipitation will affect heads within the model domain. As discussed in the October 10, 1991 memo by Swift in Volume 3, Appendix A, this uncertainty includes uncertainty in the location and extent of the recharge area for the Culebra, uncertainty in the relationship between precipitation and infiltration in the recharge area, and uncertainty in the flow path from the recharge area to the model domain. Future analyses will examine the sensitivity of the groundwater-flow model to uncertainty in the recharge scaling factor, to the assumptions made in determining the location and range of the prescribed head variations, and to the assumptions made in selecting the parameter values controlling the future precipitation function.

Radionuclide Transport in the Culebra Dolomite

Analysis of hydrologic tests indicates that in regions of relatively higher transmissivity, the Culebra Dolomite behaves as a dual-porosity medium, with solute transport occurring in both fractures and matrix porosity (Kelly and Pickens, 1986; Saulnier, 1987; Beauheim, 1987a,b,c, 1989). The performance-assessment model for transport uses the Darcy velocity field calculated by the local groundwater-flow model and allows for retardation during transport both by diffusion and sorption in matrix porosity and sorption by clays that line fractures.

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 to calculate the partitioning of radionuclides between groundwater and rock. Distribution coefficients 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 and the nature of the flow system, experimental data cannot be extrapolated directly to a complex natural system. For the 1990 preliminary performance assessment, cumulative distribution functions (cdfs) for K_ds were estimated from experimental and theoretical work (Siegel, 1990). Distributions were then derived for retardation factors, which are defined as mean fluid velocity divided by mean radionuclide velocity and which take into account pore space geometry and the thickness of clay linings as well as K_d values. The derivation of retardation factors for the 1991 calculations is discussed in Volume 3 of this report.

Sensitivity analyses performed as part of the 1990 preliminary performance assessment indicated that, conditional on the models and distributions used in the 1990 calculations, variability in retardation factors was the second most important contributor (after radionuclide solubility in repository brine) to overall variability in cumulative releases through groundwater transport (Helton et al., 1991). Because the major source of uncertainty in retardation factors is in the estimation of K_ds and because directly applicable experimental data are not available, the WIPP performance-assessment team organized an expert panel to provide judgment about probability distributions for K_d values to be used in the 1991 preliminary performance assessment. Unlike other expert panels organized for WIPP performance assessment (e.g., the future intrusion panel discussed in Chapter 4 of this volume and the source term panel discussed later in this chapter), this panel consisted of SNL staff members who are currently working on retardation in the Culebra or who have done so in the past. In other regards, procedures for the presentation of the issues and the elicitation of results were as suggested by Hora and Iman (1989) and Bonano et al. (1990), as described in Chapter 4 of this volume.

The radionuclide retardation expert panel was requested to provide probability distributions for distribution (sorption) coefficients for eight elements (americium, curium, uranium, neptunium, plutonium, radium, thorium, and lead) that represent a spatial average over the total area of concern (kilometers from the repository). This was to be done for two separate cases: (1) the coefficients that result from the clay that lines the fractures in the Culebra Dolomite, and (2) the coefficients that result from the matrix pore space of the Culebra Dolomite. During the meetings, the panelists decided to further break down the problem by examining the coefficients that would result from the particular rock species and two different transport fluids: (1) transport fluid that is predominantly relatively low-salinity Culebra brine, or (2) transport fluid that is predominantly high-salinity Salado brine. Probability distributions were thus provided for four situations for each radionuclide.

Two short meetings were held in April 1991 to discuss the physical situation and the issue statement. The period between the second and third meetings (approximately one month) was available for the panelists to examine the existing data base and discuss the results with each other. The third meeting, held at the end of May 1991, involved the expert judgment elicitation training, a discussion among the panelists as to the cases and assumptions to be used during the elicitation, and the actual elicitation sessions. The experts were elicited separately, at the request of one of the panelists. Each panelist provided distributions where they were able. Incompleteness resulted in some cases from a lack of knowledge about a particular radionuclide. Specific distributions provided by each panelist are presented in Volume 3 of this report, together with the composite distributions used in the 1991 performance-assessment calculations.

5.2 The Engineered Barrier System

The WIPP disposal system includes engineered barriers that minimize the likelihood of radionuclides migrating through the hydrogeologic setting to the accessible environment. As presently designed, the repository relies on seals in panels, drifts, and shafts to prevent migration through the excavated openings. If performance assessments indicate additional barriers are needed to reduce potential radionuclide transport up an intrusion borehole, modifications can be made to the form of the waste and backfill or to the design of the waste-disposal areas that will assure acceptable long-term performance.

5.2.1 THE SALADO FORMATION AT THE REPOSITORY HORIZON

Although the stratigraphy of the Salado Formation is consistent over much of the Delaware Basin, there are important vertical variations in lithology. Because these lithologic layers are close to horizontal at the WIPP, the repository is being excavated within a single stratigraphic horizon (rather than at a constant elevation) so that all panels within the waste-disposal area share the same local stratigraphy. As a result, the floor of the waste-disposal area will slope slightly (less than 1°) to the southeast, and there will be a difference in elevation between the highest and lowest panels of less than 10 m (33 ft).

Panels are excavated entirely within a 7.3-m (24-ft)-thick section of halite and polyhalite (Figure 5-17). Below this section and approximately 1.25 m (4 ft) below the floor of the panels lies Marker Bed 139 (MB139), which contains approximately 0.9 m (3 ft) of anhydrite with clay seams. Above the repository horizon and approximately 2.1 m (7 ft) above the roof of the panels lies anhydrite B, an approximately 6-cm (2.4-in)-thick anhydrite and clay seam. Anhydrite A, approximately 21 cm (8.3 in) of anhydrite with clay, is another 1.8 m (6 ft) above anhydrite B. A more detailed description of the stratigraphy is provided in Volume 3 of this report.

Excavation of the repository and the consequent release of lithostatic stresses has created a disturbed rock zone (DRZ) around the underground openings. The DRZ at the WIPP has been confirmed by borehole observations, geophysical surveys, and gas-flow tests, and varies in extent from 1 to 5 m (3.3 to 16.4 ft) (Stormont et al., 1987; Peterson et al., 1987; Lappin et al., 1989). Fractures and microfractures within the DRZ have increased porosity and permeability of the rock and increased brine flow from the DRZ to the excavated openings (Borns and Stormont, 1988, 1989). Fracturing has occurred in MB139 below the excavated areas and in both anhydrites A and B above the excavated area. It is not known how far fracturing in MB139 and the anhydrites A and B extends laterally from the excavations at this time, nor is the ultimate extent of the DRZ known. Most deformation related to development of the DRZ is believed to occur in the first five years after excavation (Lappin et al., 1989).

Fracturing in the DRZ, particularly in MB139 and the anhydrite layers, may provide a pathway for fluid migration out of the repository and possibly around panel and drift seals. Characterization of fracture-related permeability in these layers is essential to modeling of two-phase (gas and brine) fluid flow into and out of the repository.

5.2.2 REPOSITORY AND SEAL DESIGN

Major components of repository design that affect performance assessment are the waste itself, the underground waste-disposal area and its access drifts and shafts, and the seals that will be used to isolate the disposal area when the repository is decommissioned. The underground workings will ultimately consist of eight waste-disposal panels, access drifts and shafts, and an experimental area (Figure 5-18). Drifts in the central portion of the repository will also be used for waste disposal, providing the equivalent of an additional two panels for waste disposal. A more detailed discussion of repository design is available in Volume 3 of this report.

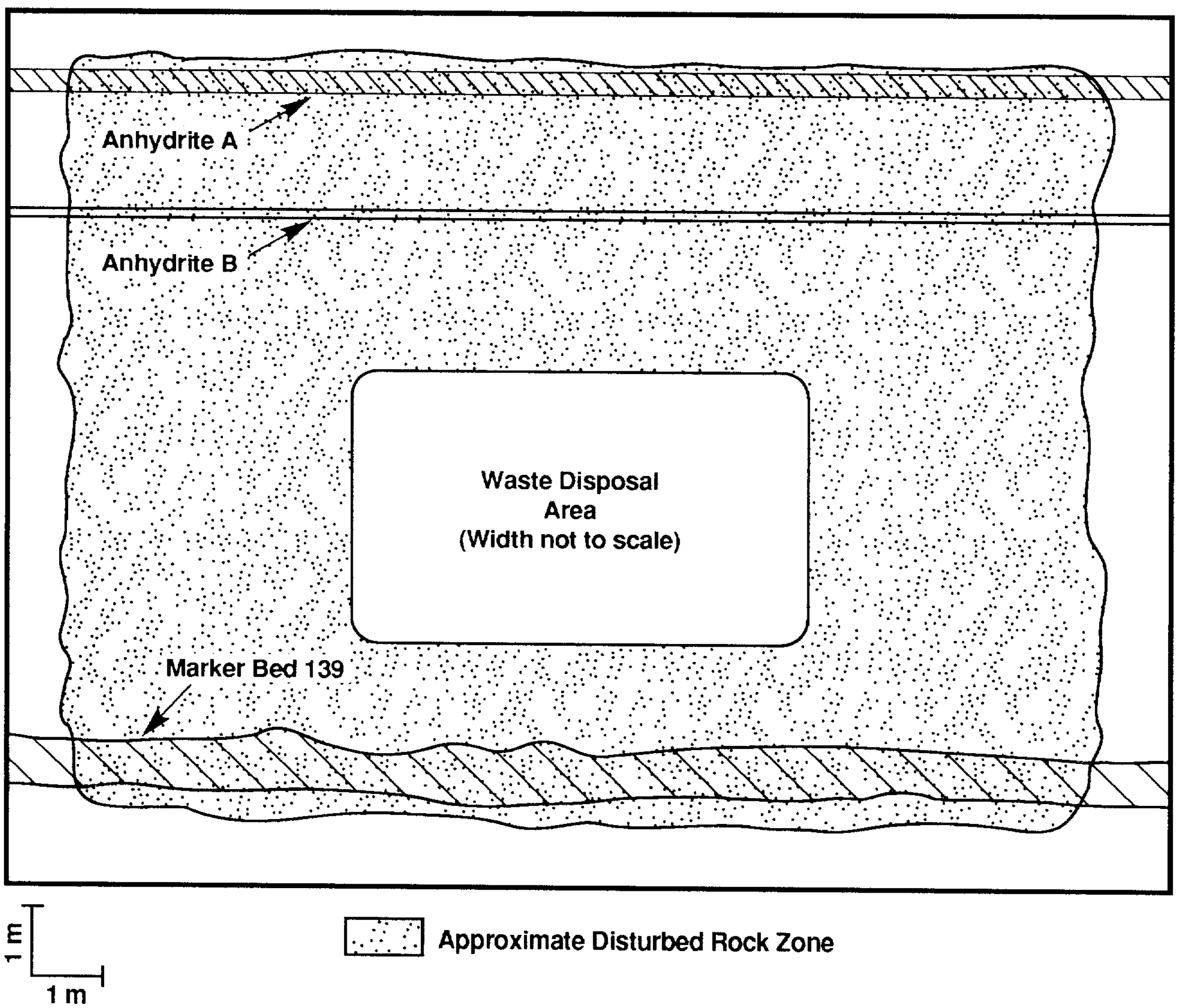


Figure 5-17. Schematic Cross Section of Salado Formation Stratigraphy at the Waste-Disposal Horizon.

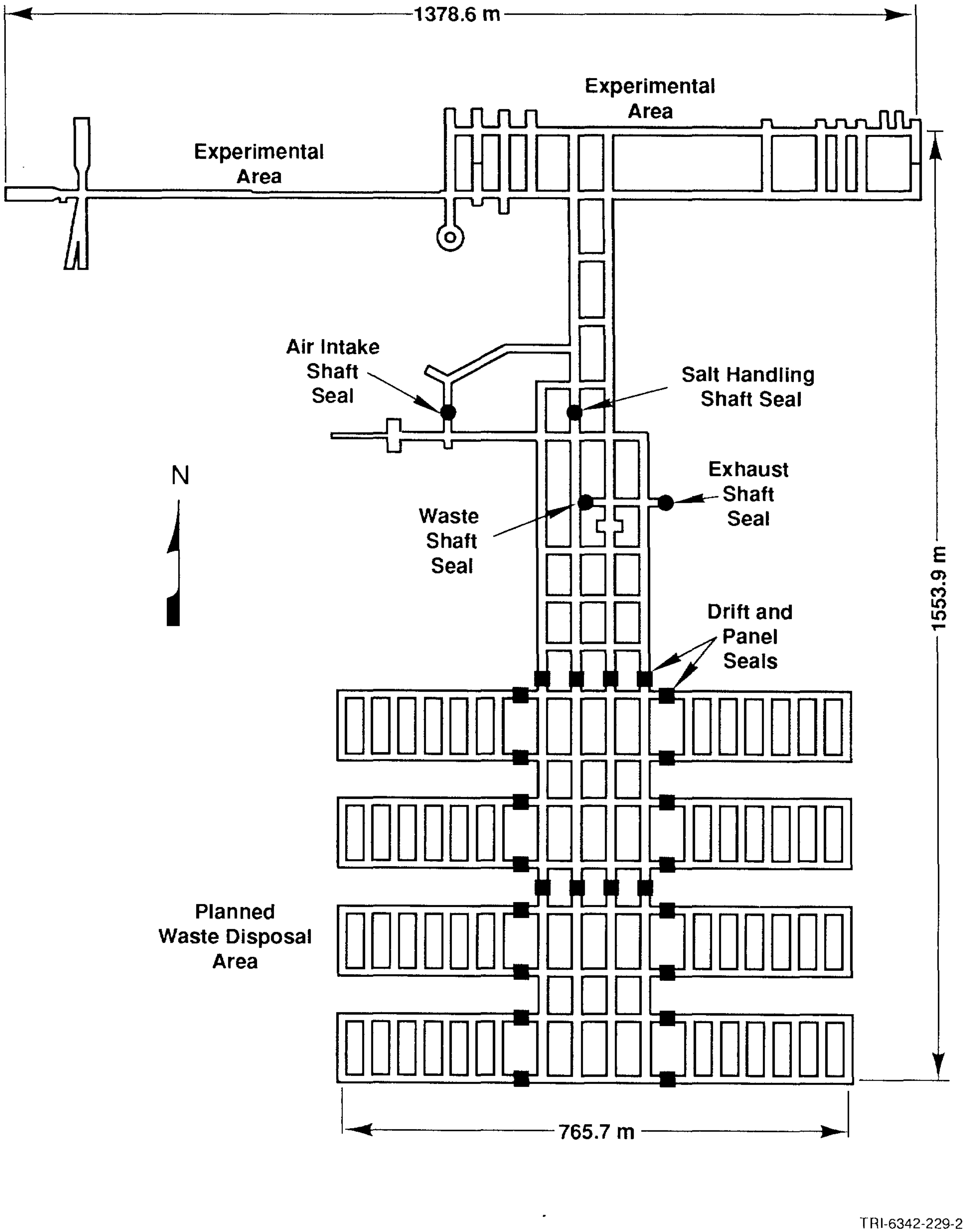


Figure 5-18. Plan View of Waste-Disposal Horizon Showing Shaft, Drift, and Panel Seal Locations (after Stormont, 1988).

All underground horizontal openings are rectangular in cross section. The disposal area drifts, in the southern part of the repository, are 4.0 m (13 ft) high by 7.6 m (25 ft) wide; the disposal rooms are 4.0 m (13 ft) high, 10.1 m (33 ft) wide, and 91.4 m (300 ft) long. Pillars between rooms are 30.5 m (100 ft) wide. The eight waste-disposal panels will each have an initial volume of 46,000 m^3 (1.6×10^6 ft^3). The northern drift disposal area will have an initial volume of 34,000 m^3 (1.2×10^6 ft^3), and the southern drift disposal area will have an initial volume of 33,000 m^3 (1.2×10^6 ft^3) (Rechard et al., 1990a). Overall, the waste-disposal areas will have an initial volume of about 435,000 m^3 (1.5×10^7 ft^3).

The four access shafts are cylindrical and range in diameter from 5.8 m (19 ft) to 3.0 m (10 ft). Shafts are lined in the units above the Salado Formation to prevent groundwater inflow and provide stability; they are unlined in the salt.

Excavation of the first waste-disposal panel is complete; the remaining panels will be excavated as needed. Waste will be emplaced within the panels in drums or metal boxes, and panels will be backfilled and sealed as they are filled. Seals will be installed in panels, drifts, and the vertical shafts before the repository is decommissioned. Waste, backfill, and seals will be consolidated by creep closure after decommissioning.

Waste Characterization

The waste that will be emplaced in the WIPP must meet Waste Acceptance Certification requirements (draft of WIPP-DOE-069-Rev. 4, as explained in Chapter 1 of this volume). These requirements include that waste material containing particulates in certain size and quantity ranges will be immobilized, liquids are restricted to that remaining in well-drained containers, radionuclides in pyrophoric form are limited to less than one percent by weight of the external container, and no explosives or compressed gases are permitted. Ignitable, corrosive, and reactive wastes are not acceptable at the WIPP.

The current design of the WIPP has a total emplacement volume for CH-TRU waste of 6.2×10^6 ft^3 (approximately 175,000 m^3) (U.S. DOE, 1980a). The estimate of the volume of CH waste supplied by the 10 generator sites for the 1990 IDB (Integrated Data Base) was approximately 100,000 m^3 (U.S. DOE, 1990e). Current performance-assessment calculations use an initial CH-waste inventory based on the design volume for waste emplacement. To estimate the characteristics of the CH inventory for a design capacity, the 1990 IDB estimated volumes were scaled up by 64.9 percent by volume to equal the design volume. The stored waste in the 1990 IDB only represents about 34 percent of the design volume. Since 66 percent of the waste volume has not been generated, the waste characterization must be considered an estimate with a potentially large uncertainty.

An estimation of the characterization of the CH waste for the current performance-assessment calculations was based on a scale up of weights estimated from 1987 waste characterization information (Drez, 1989). The 1987 detailed waste characterization information was used because a later update is not currently available. Based on the design capacity of the WIPP and average weights (Butcher, 1989) for the combustibles (plastics and cellulosics) and metals and glass constituents, estimates of about 13,000,000 kg of combustibles and 20,000,000 kg of metals and glass were calculated. Using the percentages of the detailed constituents in the 1987 estimated inventory and the total weight of combustibles and metals and glass for the design capacity, estimates of the total weights of the aluminum, steel, paper, cloth, wood, plastics, rubber, and other detailed constituents in CH waste for the design volume were made. The weights of metals, plastics, cellulosics, and rubbers are required for performance assessment because they may influence gas generation and potential radionuclide transport.

The weight of waste containers, drums, and boxes, and of container liners must be estimated because they also affect gas-generation potential. It was assumed in the estimation of the container weights that only 55-gallon drums and standard waste boxes will be emplaced in the WIPP. These are the only containers that can currently be transported in a TRUPACT-II (NuPac, 1989). Based on a design capacity and the assumption about the containers, it was estimated that about 532,500 drums and 33,500 standard waste boxes would be emplaced in the WIPP. The total weight of the steel in the containers is larger than the estimated total weight of metals and glass in the waste inventory.

The estimates of the total weights of the constituents in the wastes for these analyses were larger than the weights estimated for the analyses discussed in Lappin et al. (1989). This increase was primarily the result of scaling the volume of the waste to a design volume of about 175,000 m^3. Lappin et al. (1989) used a volume of 556,000 drum equivalents, which is about 115,000 m^3. The increase in the weights of the constituents also resulted from an increase in the estimates reported by Drez (1989) from an earlier inventory provided in Lappin et al. (1989).

Seals

Seals will be emplaced in the entrance to each panel, in two locations within the drifts between the panels and the vertical shafts, and in each of the four vertical shafts (Figure 5-18, 5-19) (Nowak et al., 1990). Design of these seals reflects specific functions for each type of seal. Seals in the

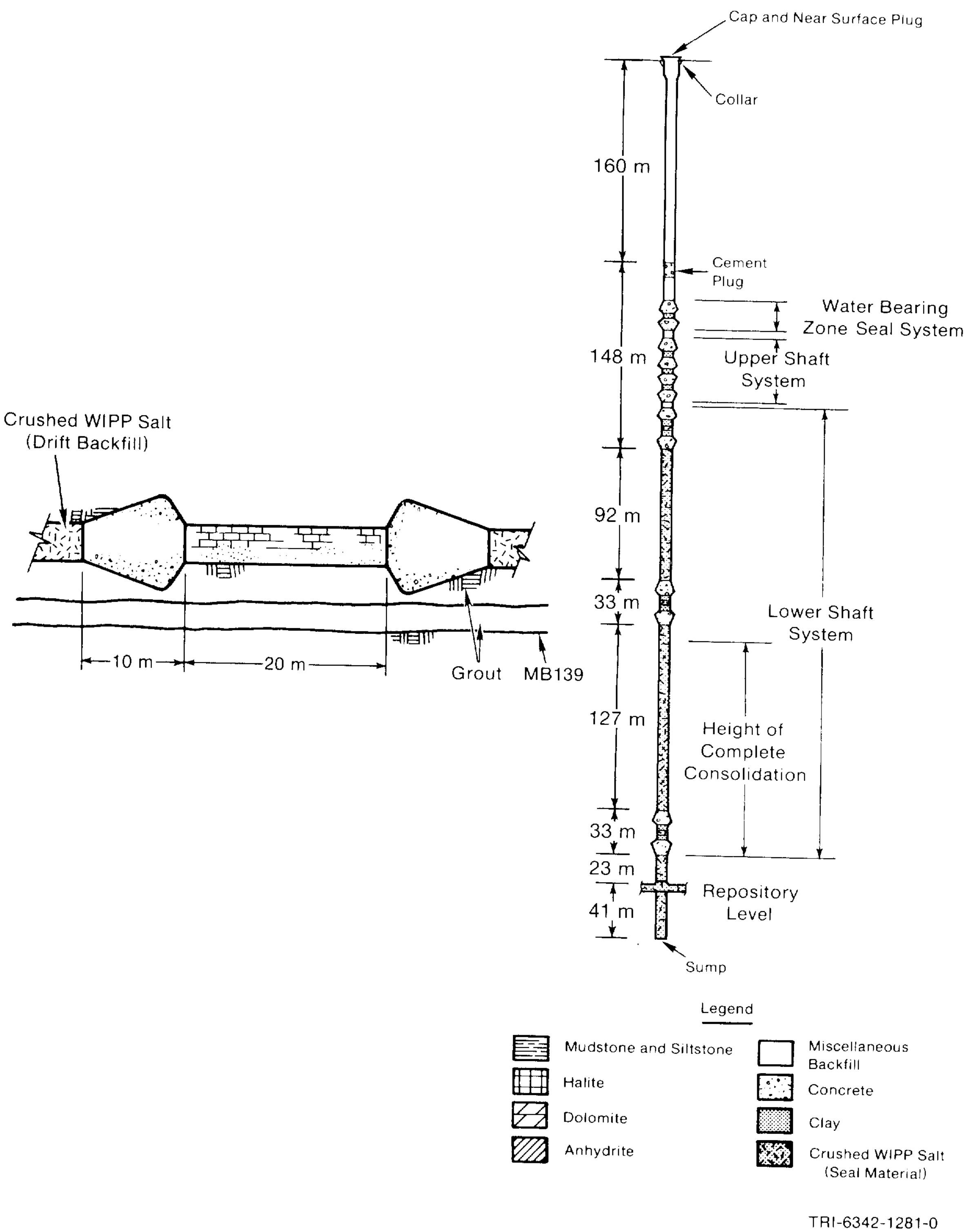


Figure 5-19. Representative Shaft and Plug Seals (after Nowak et al., 1990). Vertical distances based on stratigraphy in ERDA-9.

upper portion of the shafts must prevent groundwater flow from the water-bearing units of the Rustler Formation from reaching the lower portions of the shafts and the waste-disposal areas. Seals in the lower portion of the shafts must provide a long-term, low-permeability barrier that will prevent Salado Formation brine from migrating up the shaft. Panel seals (and drift seals) prevent long-term migration of radionuclide-contaminated brine through the drifts to the base of the shafts and must also provide safe isolation of radionuclides during the operational phase of the repository.

The primary long-term component of both lower shaft and panel seals will be crushed salt, confined between short-term rigid bulkheads that will prevent fluid flow while creep closure reconsolidates the crushed salt to properties comparable to those of the intact Salado Formation. The short-term seals will be concrete in the panels and drifts, and composite barriers of concrete, bentonite, and consolidated crushed salt in the shafts. Crushed salt in the long-term portion of the seals will be preconsolidated to approximately 80% of the density of the intact formation and will compact further to approximately 95% of initial density within 100 years, at which time permeabilities are expected to be comparable to those of the undisturbed rock (Nowak and Stormont, 1987). Panel seals will be 40 m (131 ft) long, with 20 m (66 ft) of preconsolidated crushed salt between two 10-m (33-ft) concrete barriers. Shaft seals will extend the full length of the shafts and will include composite barriers at the appropriate depths to individual lithologic units, including the Culebra Dolomite (Nowak et al., 1990). Additional information about seal design is presented in Volume 3 of this report.

Marker Bed 139 will be sealed below each panel and drift seal by grouting, either with crushed-salt-based grout, cementitious material, or bitumen. Other anhydrite layers will be sealed similarly. Salt creep is expected to close fractures in halite in the DRZ over time, and engineered seals are not planned for the DRZ outside of MB139 and other interbeds.

Backfill

Void space between waste containers and elsewhere in the underground workings will be backfilled before sealing and decommissioning (Tyler et al., 1988; Lappin et al., 1989). This backfill will reduce initial void space and permeability in the panels and will consolidate under pressure to further limit brine flow through the waste. Performance-assessment calculations to date have assumed a backfill material of pure crushed salt, which will not sorb radionuclides. Design alternatives for backfill that include bentonite as an additional barrier to retard radionuclides are under consideration (WEC, 1990; U.S. DOE, 1990d), and will be evaluated in future performance assessments.

Engineered Alternatives

The WIPP has been designed to dispose of waste in the form in which it is shipped from the generator sites. Preliminary performance-assessment calculations indicate that modifications to the waste form that limit dissolution of radionuclides in brine have the potential to improve predicted performance of the repository (Marietta et al., 1989; Bertram-Howery and Swift, 1990). Modifications to the backfill and design of the room could also reduce radionuclide releases. Modifications could also, if needed, mitigate the effects of gas generated within the repository. Present performance assessments are not complete enough to determine whether or not such modifications will be needed for regulatory compliance, but the DOE is proceeding with investigations of engineered alternatives to waste form and repository design so that alternatives will be available if needed (U.S. DOE, 1990a). The Engineered Alternatives Task Force (EATF), assembled by Westinghouse Electric Corporation, has identified 19 possible modifications to waste form, backfill, and room design that merit additional investigation (WEC, 1990; U.S. DOE, 1990d). The 1991 performance-assessment calculations do not include simulations of these alternatives. Selected alternatives will be examined in future performance-assessment calculations, however, to provide guidance to DOE on possible effectiveness of modifications.

5.2.3 THE RADIONUCLIDE INVENTORY

The radionuclide inventory for CH- and RH-TRU waste was estimated from input to the 1990 IDB (U.S. DOE, 1990e). Twelve radionuclides were identified to be in the initial CH inventory. The estimates from the 1990 IDB were based on a volume of 106,458 m^3. To estimate the curie content of the initial inventory for a design capacity, the 1990 estimated curie contents were scaled up by 64.9 percent by volume to equal the design volume. This scaling results in an initial total CH inventory of about 16,000,000 curies. Based on a design volume, the majority of the CH waste has not been generated; therefore, the radionuclide inventory is an estimate based on currently available information and has the potential for large uncertainty. The stored and newly generated RH volume in the 1990 IDB sum to a total of 5,344 m^3. The containers that will be placed in an RH canister have a different volume depending on the generator site; therefore, a canister may not contain 0.89 m^3 of RH waste. The U.S. DOE (1991c) identifies that the submittal to the 1991 IDB totals 7,622 canisters. The total volume based on the number of canisters is 6,784 m^3. The 1990 IDB indicates there may be a considerable volume of uncharacterized waste that will probably be RH. Because of the uncertainty in the RH inventory, the smaller total volume of waste and not the volume of canisters was used as a scaling factor to estimate the RH design radionuclide inventory for these analyses. The total RH inventory was estimated to be about 1,600,000 curies. Details of the radionuclide inventory are presented in Volume 3 of this report.

Radioactive decay within the repository is simulated with a nearly complete set of decay chains, which are given in Volume 3 of this report. Decay is simulated for 20 radionuclides in the CH inventory and for an additional 3 radionuclides in the RH inventory. Only those radionuclides with short half-lives are omitted. Decay during 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 toxicity, and low activity (less than 100 curies at 10,000 years). This simplification did not eliminate radionuclides that could cause significant health effects.

The only radioactive gas expected in the repository is radon-222, created from the decay of radium-226. Decay of thorium-230 will cause the amount of radium-226 to increase from about 0 to 23 curies in a panel at 10,000 years. Because radon-222, with a half-life of only 3.8 days, will exist in secular equilibrium with radium-226, its activity will be insignificant throughout the 10,000-year period. Not including releases of volatile radionuclides should not significantly affect the total radionuclide release.

5.2.4 RADIONUCLIDE SOLUBILITY AND THE SOURCE TERM FOR TRANSPORT CALCULATIONS

Previous WIPP performance assessments have calculated the source term for transport modeling using the same estimated range and distribution (loguniform from 10^{-9} to 10^{-3} M) for the solubility limit of all radionuclide species in repository brine (Lappin et al., 1989; Brush and Anderson, 1989). Sensitivity analyses performed as part of the 1990 preliminary performance assessment indicated that, conditional on the models and distributions used in the 1990 calculations, variability in the solubility limit was the most important single contributor to variability in total cumulative releases to the accessible environment resulting from groundwater transport (Helton et al., 1991). In the absence of experimental data that might better define solubility limits, a panel of experts external to the WIPP Project was convened to provide the performance-assessment team with judgment about solubility limits for specific elements under variable Eh and pH conditions.

Selection of the panel and elicitation of their judgment followed the procedure suggested by Hora and Iman (1989), described in Chapter 4 of this volume in the discussion of the future-intrusion panel. Candidates for the expert panel on source term were gathered by a two-tiered nomination process. Initial nominations were solicited from an SNL staff member and a university consultant, as well as from members of the Performance Assessment Peer Review

Panel and the National Research Council's WIPP Panel. Additional nominations were requested from all those contacted. Curriculum vitae from those who were interested in participating in such a panel and available during the entire study period were reviewed by a two-member selection committee external to SNL. Some individuals removed themselves from consideration because of prior time commitments, current contracts with SNL, a self-determined lack of expertise, or involvement in an oversight organization. Nominees were evaluated on the basis of expertise and professional reputation, and four experts were selected whose complementary areas of specialization provided the needed breadth and balance to the panel.

Rather than considering the solubility limit of the radionuclides (as was used in the 1990 calculations in lieu of concentrations), the panel was instead asked to consider explicitly the individual radionuclide concentrations that might be expected. Specifically, panel members were asked to develop probability distributions for the dissolved concentration of americium, curium, uranium, neptunium, plutonium, radium, thorium, and lead in the WIPP brines in the repository rooms and drifts (with all that implies in terms of waste and room chemistry). They were also requested to repeat the process for the concentration due to suspended materials, which was not distinguished from the dissolved fraction in the 1990 calculations.

The radionuclide source term expert panel met twice in Albuquerque during March and April 1991 and communicated with each other throughout the study period as they saw fit. The first meeting was used to acquaint the experts with the WIPP, the SNL effort in performance assessment, and the issue statement. The panelists were provided with one-half day of training in expert-judgment/probability elicitation, which is the process whereby experts are assisted in developing probability distributions by individuals experienced in decision analysis and the expert-judgment process.

The second meeting included presentations by each panelist of his or her approach in responding to the issue statement. Further discussion led to the panelists' decision to be elicited as a group in order to benefit from each panelist's particular expertise. Being elicited together required the development of a group strategy for creating the probability distributions. The panel developed a strategy based on basic solubility principles; related experimental data, where available; consideration of the impact on the concentration due to changes in environmental factors (e.g., changes in pH); and expert judgment in synthesizing the above. Individual uncertainty cannot be distinguished in a single distribution but resulted in a larger range for the composite distribution. Greater detail in the description of the panel's methodology can be found in Trauth et al. (1991). The probability distributions created by the panel are contingent upon other circumstances, such as the oxidation state of the radionuclide or the presence of other compounds (carbonate or sulfate). Eh versus pH diagrams were provided for those radionuclides for which more than one oxidation state was thought possible. The probability distributions can be found in Trauth et al. (1991) and are reproduced in Volume 3 of this report. These distributions reflect concentrations of dissolved materials only: the panelists concluded that available data was insufficient to provide judgment about concentrations of suspended materials.

As a step in reducing the uncertainty in the estimates, the expert panel developed distributions for each specific radionuclide of interest. In addition, where the repository conditions might lead to the existence of more than one oxidation state for a radionuclide or more that one solid species containing the radionuclide (based on the presence or absence of specific complexants--carbonate and sulfate), more than one distribution was developed for a specific radionuclide. The ranges of some of the distributions developed by the panel are larger and some are smaller than the distributions used in the 1990 calculations, and the ranges reflect greater or lesser concentrations. Variations reflect differences in the chemistry of the specific radionuclide in the presence of WIPP waste and the standard A brine for the WIPP (Molecke, 1983; Lappin et al., 1989, Table 3.4).

5.2.5 PERFORMANCE-ASSESSMENT MODEL FOR THE REPOSITORY/SHAFT SYSTEM

The performance-assessment model for the repository/shaft system must simulate migration of radionuclides and hazardous materials away from the repository through all pathways. Specifically, the model simulates liquid and gas flow in the Salado Formation, particularly in the interbeds, as a function of the various processes active in the waste-disposal panels, including borehole intrusion. The model also calculates a time-dependent source term of radionuclide concentrations in repository brine for transport modeling in the Salado Formation and the overlying Culebra Dolomite.

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. Free brine initially will not be present within the disposal area, and void space above the backfilled waste will be air-filled (Figure 5-20a). Brine seepage from the Salado Formation will have filled fractures in MB139 beneath the disposal area (Lappin et al., 1989; Rechard et al., 1990b).

Following decommissioning, salt creep will begin to close the repository (Figure 5-20b). In the absence of elevated gas pressures within the repository, modeling of salt creep indicates that consolidation of the waste

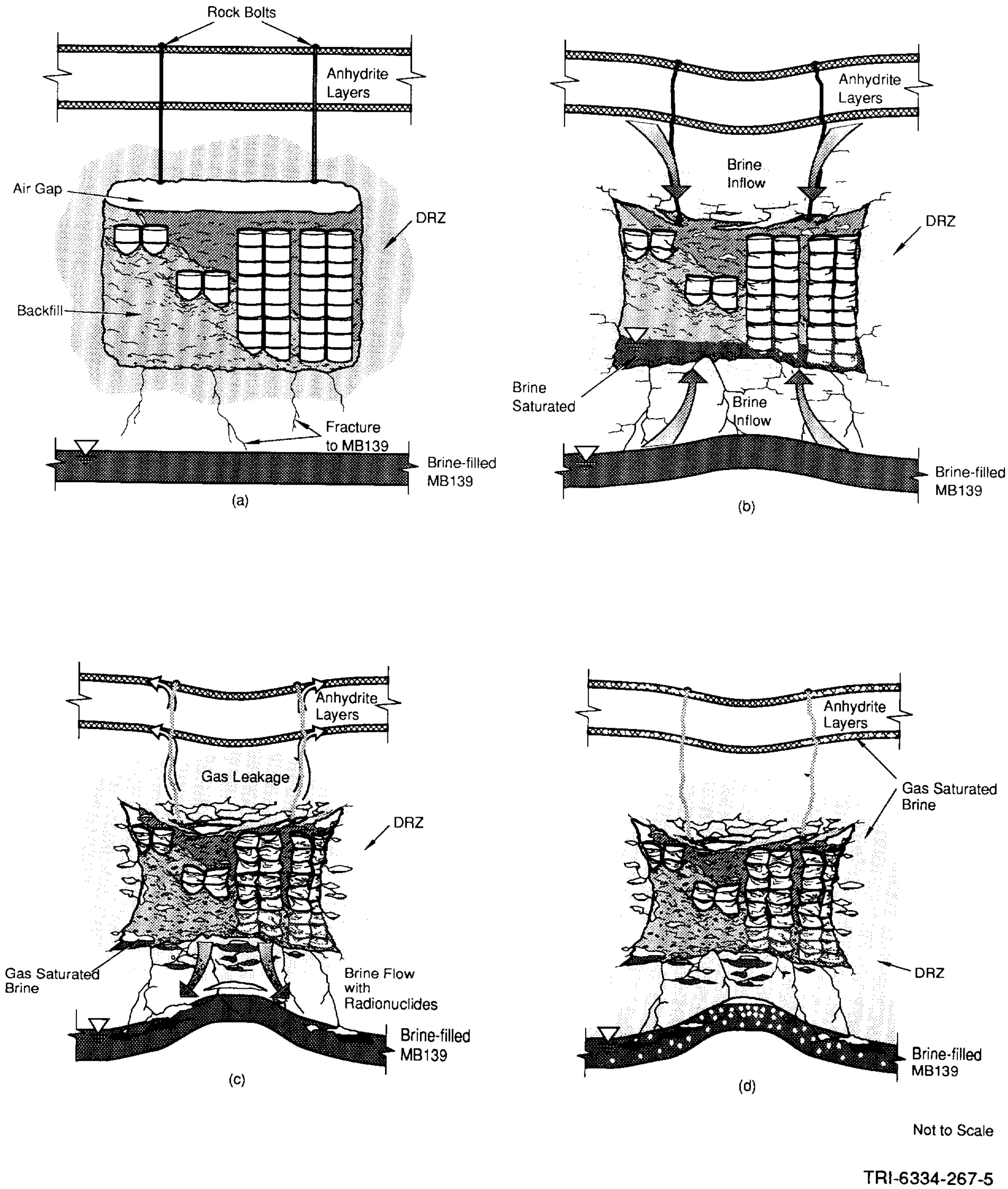


Figure 5-20. Hypothesized Episodes in Disposal Area During Undisturbed Conditions. This drawing shows (a) initial conditions after decommissioning; (b) conditions after room creep closure and brine inflow; (c) conditions after gas generation, brine outflow, and room expansion; and (d) undisturbed conditions with gas-filled room surrounded by gas-saturated brine (Rechard et al., 1990b).

in unreinforced rooms could be largely complete within 100 years (Tyler et al., 1988; Munson et al., 1989a,b). Brine will seep into the disposal area from the surrounding salt, however, and gas will 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 5-20c). 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 5-20d).

All of the major processes active in the waste-disposal area 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, 1988b). 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 immiscible flow through a porous medium. Other possibilities 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 5-21a,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 5-21c).

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

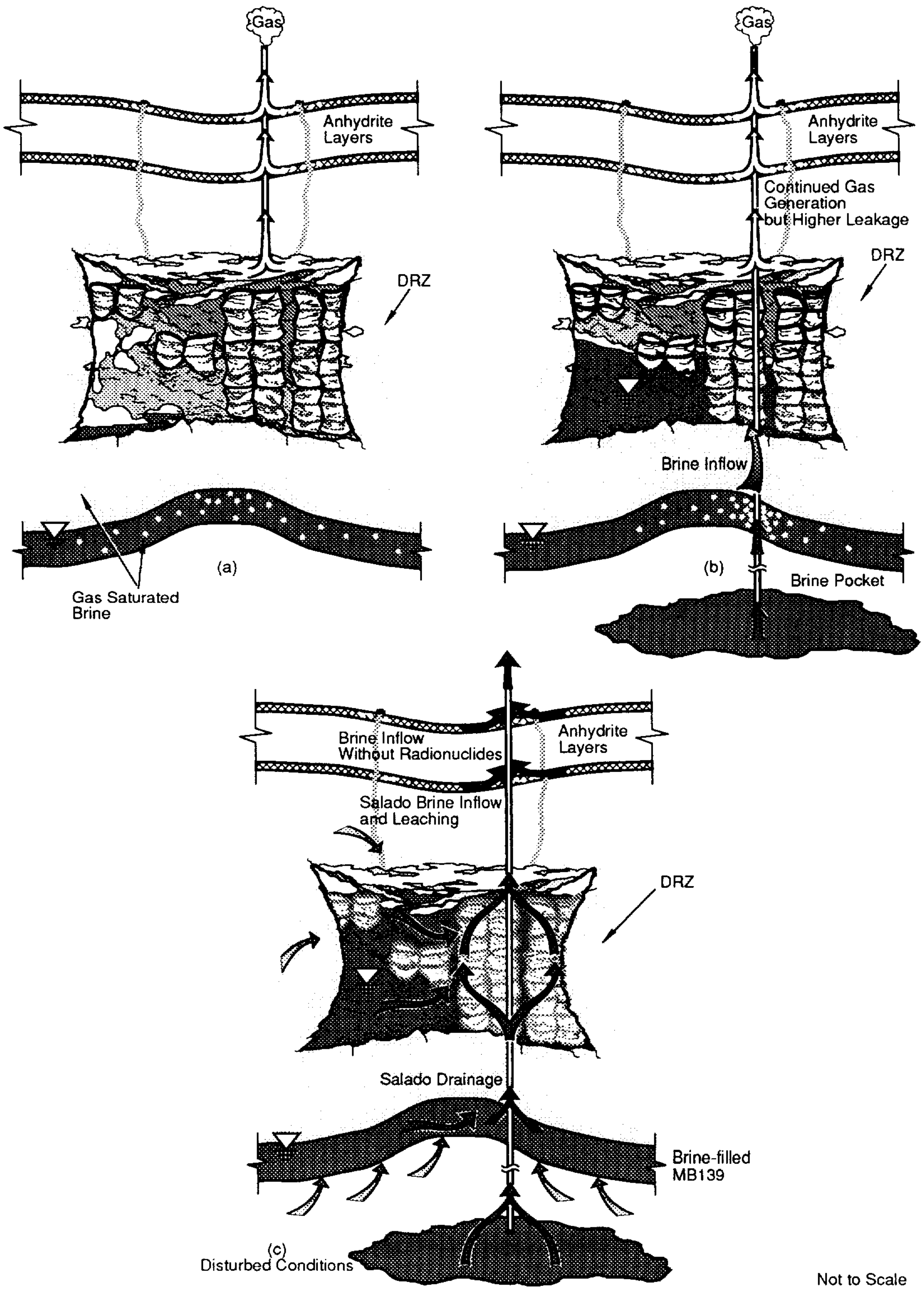


Figure 5-21. Hypothesized Episodes in Disposal Area After Human Intrusion. This drawing shows (a) initial room gas depressurization when penetrated by an exploratory borehole, (b) final gas and brine depressurization as borehole seals degrade, and (c) brine flow through the borehole to the Culebra Dolomite (Rechard et al., 1990b).

closure will be a major factor in determining waste permeability. Models and the data base 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.

Modeling of Undisturbed Performance

Modeling of the undisturbed performance of the disposal system is required to evaluate compliance with the Individual Protection Requirements of the Standard (§ 191.15) and to provide simulations of the base-case scenario for the probabilistic evaluation of compliance with the Containment Requirements of the Standard (§ 191.13). Previous estimates of undisturbed performance have indicated zero releases to the accessible environment within 10,000 years (Lappin et al., 1989; Marietta et al., 1989) (see Chapter 7 of this volume). As a result, Monte Carlo simulations of the base-case scenario are not included in the construction of the CCDFs used for preliminary comparisons with the Containment Requirements. Only those scenarios that result in releases to the accessible environment will affect the CCDF. Emphasis in modeling undisturbed performance, therefore, is on examining conservative deterministic calculations that will indicate whether or not releases could occur that would require inclusion of the base-case scenario in the Monte Carlo analysis.

Analyses of undisturbed performance reported by Lappin et al. (1989) and Marietta et al. (1989) used NEFTRAN (NEtwork Flow and TRANsport; Longsine et al., 1987), a one-dimensional flow and transport program in which the disposal system was represented by a network of discrete legs. Flow and transport was assumed to occur along MB139 to the base of the waste shaft (Figure 5-18), and then upward through the shaft seals to the Culebra Dolomite. Flow and transport was also calculated for a vertical leg through the intact Salado Formation directly to the Culebra Dolomite. The head gradient between the waste panels and the Culebra was held constant, and effects of gas generation were not considered. Neither pathway resulted in radionuclides reaching the Culebra Dolomite within 50,000 years (Marietta et al., 1989).

The 1991 preliminary assessment of undisturbed performance uses SUTRA (Saturated-Unsaturated TRAnsport; Voss, 1984) and STAFF2D (Solute Transport And Fracture Flow in 2 Dimensions; Huyakorn et al., 1989) to simulate flow and transport from the waste panels in two dimensions. Flow is assumed to occur in a single phase (brine), and gas generated within the waste panels is not included directly in the simulation. The effects of gas generation are included indirectly, however, by using elevated repository pressures calculated using the two-phase (gas and brine) flow program BOAST_II (Black

Oil Applied Simulation Tool, enhanced version; Fanchi et al., 1987). Additional details about the programs and their applications in the 1991 calculations are provided in Volume 2 of this report.

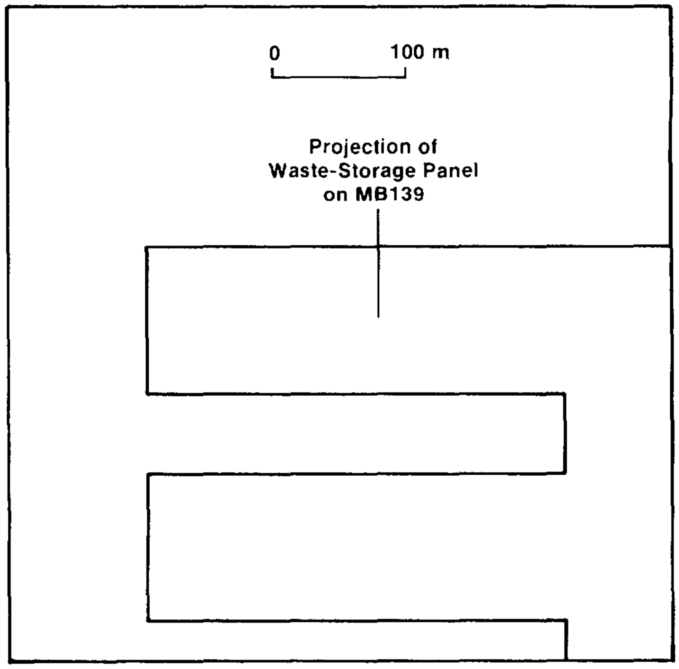
Flow and transport are simulated in two two-dimensional sections through the disposal system. One section is a horizontal plane containing the vertical projection of two waste panels onto MB139 (Figure 5-22a). This section is used to estimate lateral transport of radionuclides through the intact marker bed. The second section, a vertical profile containing a north-south drift and an access shaft, is used to estimate flow and transport along the drift and shaft pathway towards the Culebra Dolomite (Figure 5-22b). Results of these simulations are presented in detail in Volume 2 of this report and are summarized in Chapter 7 of this volume.

Modeling of Disturbed Performance

Simulations of disturbed performance use BRAGFLO (BRine And Gas FLOw; see Volume 2 of this report), a finite difference transient two-phase flow program developed for the WIPP performance assessment, to calculate brine and gas flow within a waste panel and the surrounding rock and within a borehole or boreholes connecting the panel with the Culebra Dolomite and a brine reservoir in the Castile Formation. The program PANEL (see Volume 2 of this report), also developed for the WIPP performance assessment, is used to estimate concentrations of radionuclides within repository brine and and for supplementary calculations of one-phase (brine) flow within a panel and a borehole or boreholes. Details of the programs and their application in the 1991 calculations are provided in Volume 2 of this report. Results of the simulations of disturbed performance are given in Chapter 6 of this volume.

Two-dimensional BRAGFLO simulations of two-phase (brine and gas) flow use a radially symmetric model of the disposal system with a simplified stratigraphy (Figure 5-23). Gas generation is estimated using corrosion and biodegradation reactions dependent on the availability of brine, metal, and cellulose. Gas generation ceases when reactants are consumed. Material property parameter values (e.g., porosity and absolute and relative permeability) are assigned to each of units in the simplified stratigraphy. Far-field pore pressure is held constant through time, and pressure in the repository is calculated dependent on the gas-generation rate and two-phase flow in the units shown in Figure 5-23, including the waste panel, the intact and disturbed halite and anhydrite layers, the Castile brine reservoir, the Culebra Dolomite, and the intrusion borehole.

For the 1991 preliminary comparison, uncertain parameters sampled for BRAGFLO flow simulations were porosities, permeabilities, and threshold pressures for the intrusion borehole and disturbed and undisturbed anhydrite (in anhydrite



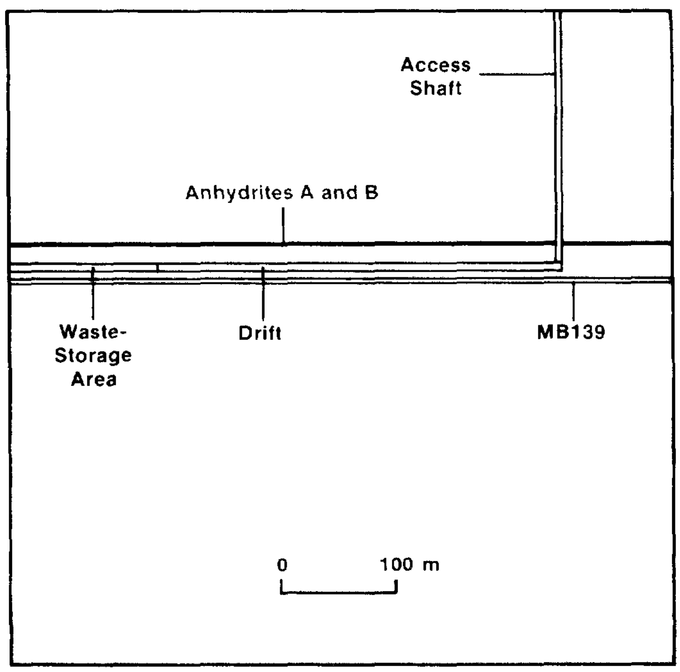


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Figure 5-22. Two-Dimensional Repository Models Used for STAFF2D and SUTRA Estimations of Radionuclide Transport during Undisturbed Conditions. Figure 5-22a is a horizontal (plan) view of the projection of two waste panels onto the plane containing MB-139. Figure 5-22b is a vertical cross section containing the waste disposal area, a north-south drift, and a vertical access shaft.

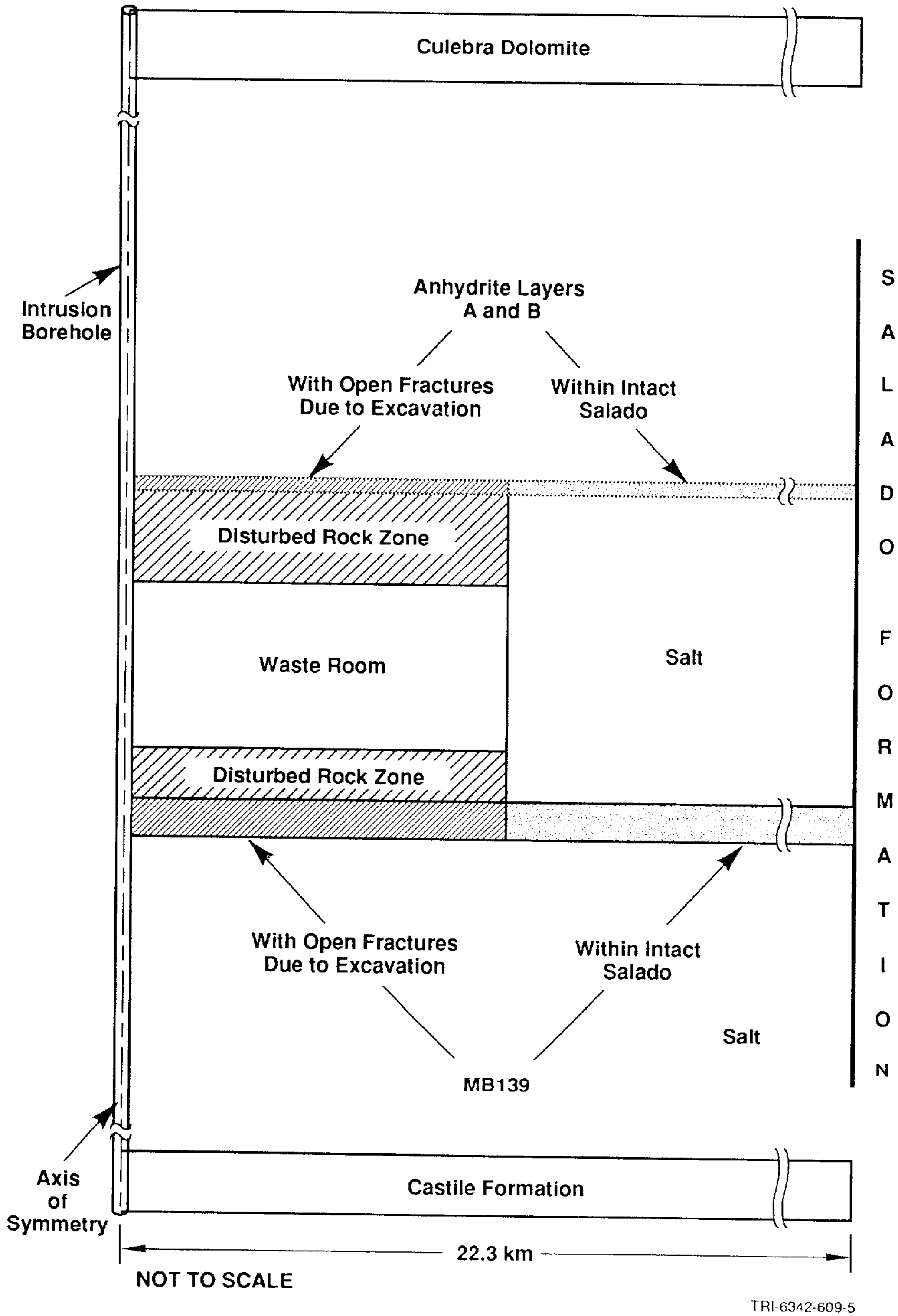


Figure 5-23. Simplified Waste-Disposal Panel Model Used in Two-Dimensional, Axially Symmetric BRAGFLO Simulations of Two-Phase (Brine and Gas) Flow (Vaughn et al., 1991).

layers A and B and in MB139), far-field pore pressure in MB139 (which was then used to fix a hydrostatic far-field pressure for all other elevations), and the initial pressure of the Castile brine reservoir. Gas-generation rates under humid and saturated conditions, the stoichiometry of the corrosion reaction, the volume fractions of the reactants (metal and cellulose), and the initial liquid saturation of the waste were also sampled. Ranges and distributions for these parameters are given in Volume 3 of this report. As described in Volume 2 of this report, reaction stoichiometry and initial volume fractions of reactants were used to derive initial room porosity and room heights.

The program PANEL estimates radionuclide concentrations in repository brine by modeling radioactive decay and dissolution within a waste panel. These calculations require an 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. The model assumes chemical equilibrium and the uniform distribution of waste within the panel. Sorption of radionuclides within the panel is not considered. For the 1991 preliminary comparison, uncertain geochemical parameters included Eh/pH conditions within the repository and solubility limits for 7 radionuclides. Ranges and distributions for these parameters are given in Volume 3 of this report.

Single-phase flow modeling using PANEL can consider four components of fluid flow separately: upward flow of brine from the Castile Formation due to the head difference between the brine reservoir and repository; brine flow from the Salado 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 is calculated using BRAGFLO, as described below. Required parameters for the Castile Formation include the initial pressure of the brine reservoir 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. All flow in PANEL is assumed to occur as in a single phase (brine) and to be governed by Darcy's law. Pressure in the Culebra Dolomite is assumed to remain constant. Change in brine reservoir pressure is assumed to be proportional to the volume of fluid discharged. All components are assumed to be at steady state with respect to boundary pressures at any given time.

Modeling of Radionuclide Releases during a Borehole Intrusion

The performance-assessment model for borehole intrusion relies on a fundamental assumption that future drilling technologies will be comparable to those of the present. The reasonableness of this assumption is unknown; without it, however, estimates of the amount of waste brought to the ground surface during an intrusion would be arbitrary and purely speculative.

If a borehole intrudes the repository, waste 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. An additional amount of waste will be brought to the surface as cavings, the material removed from the borehole wall. When the drill bit first penetrates the upper portion of a panel that is pressurized relative to the borehole with waste-generated gas, the escape of this gas may cause waste and backfill to spall into the borehole. As the borehole is extended below the repository, additional material will be eroded from the walls of the borehole at the repository horizon by the circulating fluid. Both cuttings and cavings will be transported to the surface in the circulated drilling fluid and 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 5-24). 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 has both a rotational and axial motion (Figure 5-24). 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 effective shear strength for erosion of the waste. 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. The effective shear strength for erosion of the waste 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 the effective shear strength for erosion must be determined experimentally.

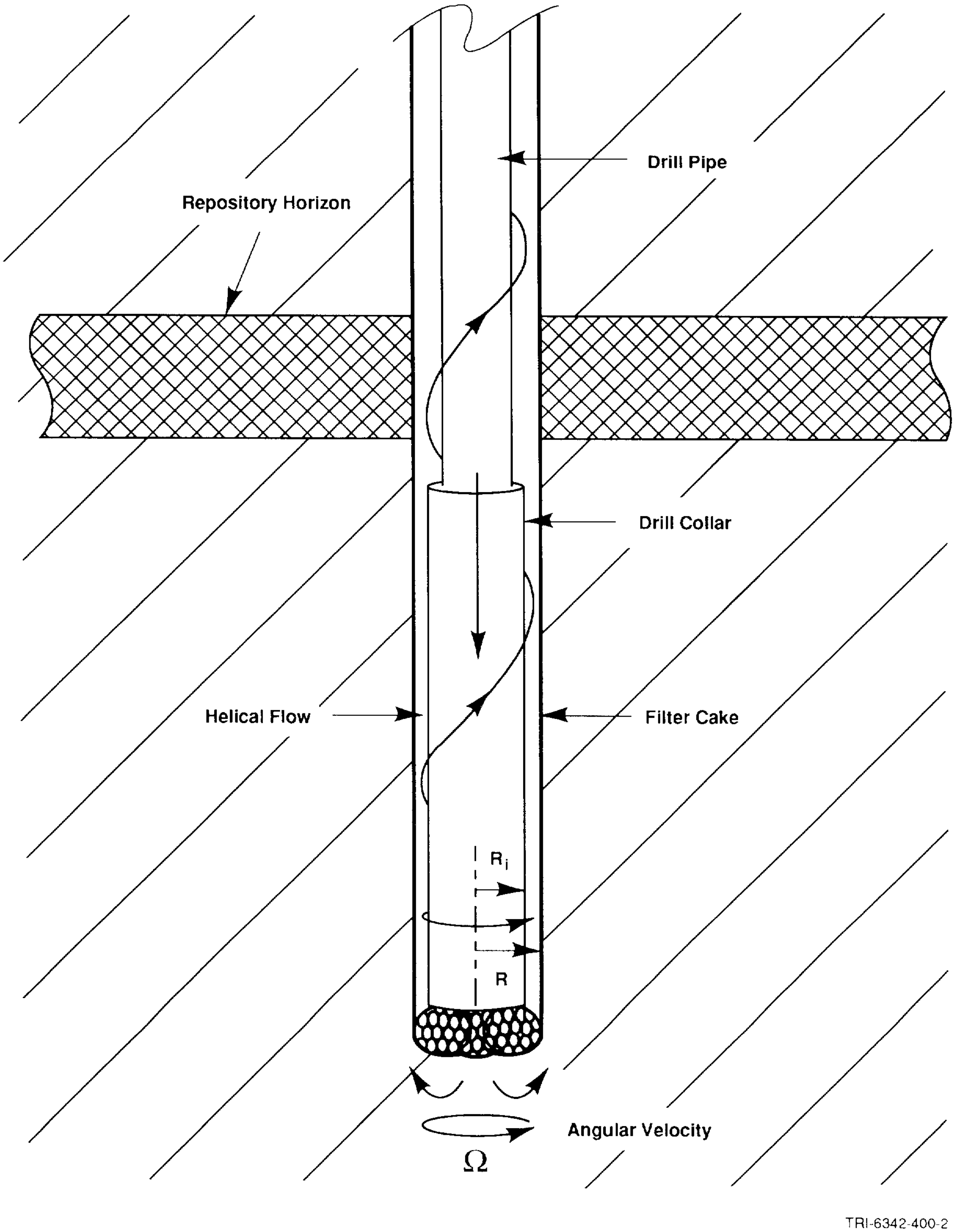


Figure 5-24. Conceptual Model of Borehole Intrusion. Not to scale (modified from Lappin et al., 1989).

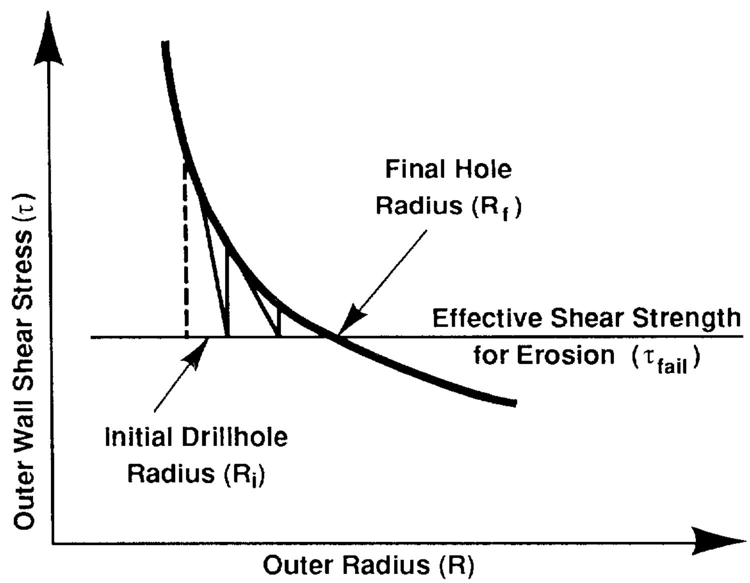
As described in more detail in Volume 2 of this report, erosion of waste will occur when the fluid shear stress at the borehole wall exceeds the effective shear strength for erosion of the waste. For any given set of conditions, the fluid shear stress at the borehole wall will be a function of annular thickness: as erosion increases hole radius, shear stress will decrease (Figure 5-25a). Erosion will cease when shear stress at the borehole wall falls below a failure-shear-stress value corresponding to the effective shear strength for erosion 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 5-25b).

The program CUTTINGS (see Volume 2 of this report) is used to simulate erosion adjacent to the drill collar using fixed values for the effective shear strength for erosion for the waste corresponding to properties of as-received waste. Drill-bit radius, which in present drilling technology is primarily a function of total borehole depth, is selected by assuming that exploratory boreholes at the WIPP will be drilled for deep gas targets (see "Drilling" in Section 4.1.4-Evaluation of Human-Induced Events and Processes in Chapter 4) and then choosing the corresponding maximum bit radius at the repository depth.

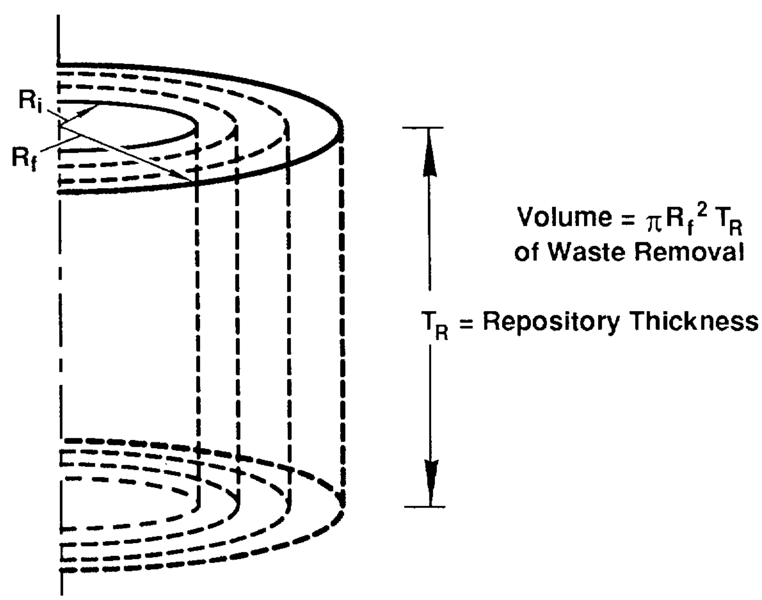
Spalling of material into the borehole is not included in the analyses by CUTTINGS. This phenomenon may occur when the drill bit penetrates repository wastes pressurized by gases generated by corrosion and biodegradation. The escape of gases to the borehole causes radial effective stresses adjacent to the borehole to become tensile. The peak tensile stress is near the borehole wall, but tensile fracturing may occur away from the borehole wall, resulting in spalling of the heterogeneous composite waste and backfill material. The process of spalling is complex, involving gas flow through a moving waste matrix with changing boundaries. As a result, estimating the quantity of spalled material is not straightforward. The importance of the contribution of spalling to the total amount of cavings is still being evaluated. For the 1991 preliminary comparison, erosion by drilling fluid, rather than spalling by waste-generated gas, is assumed to be the dominant mechanism producing cavings.

5.3 CAMCON: Controller for Compliance-Assessment System

The complexity of the compliance-assessment modeling system for the WIPP requires that calculations be controlled by an executive program (Rechard, 1989; Rechard et al., 1989). CAMCON (Compliance Assessment Methodology CONtroller) controls code linkage and data flow during lengthy and iterative consequence analyses, minimizes analyst intervention during data transfer,



a.) Relationship Between Radius and Stress



b.) Volume of Material Removed

TRI-6342-408-2

Figure 5-25. Borehole Erosion as a Function of Shear Stress.

and automatically handles quality assurance during the calculations. CAMCON currently consists of about 75 codes and FORTRAN object libraries and includes approximately 293,000 lines of FORTRAN software written specifically for the WIPP Project and another 175,000 lines of software adapted from other applications.

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. (1989).

5.3.1 DATA BASES

Three data bases, primary, secondary, and computational, are included in CAMCON. 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).

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.

The computational data base is CAMDAT (Compliance Assessment Methodology DATa). CAMDAT uses a neutral-file format 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,b, 1988; Gilkey and Flanagan, 1987). CAMDAT is fully described in Rechard et al. (1989).

5.3.2 PROGRAM LINKAGE AND MODEL APPLICATIONS

Program linkage and data flow through CAMDAT are controlled by CAMCON. Computer programs that make up the CAMCON system are major program modules, support program modules, and translators. Major program modules refer to programs that represent major tasks of the consequence modeling. Support 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. Figure 5-26 shows how programs within CAMCON are used to evaluate human-intrusion scenarios. Table 5-1 shows the status of the 79 composite programs now in CAMCON. Specific information on seven major CAMCON programs is provided Volume 2 of this report.

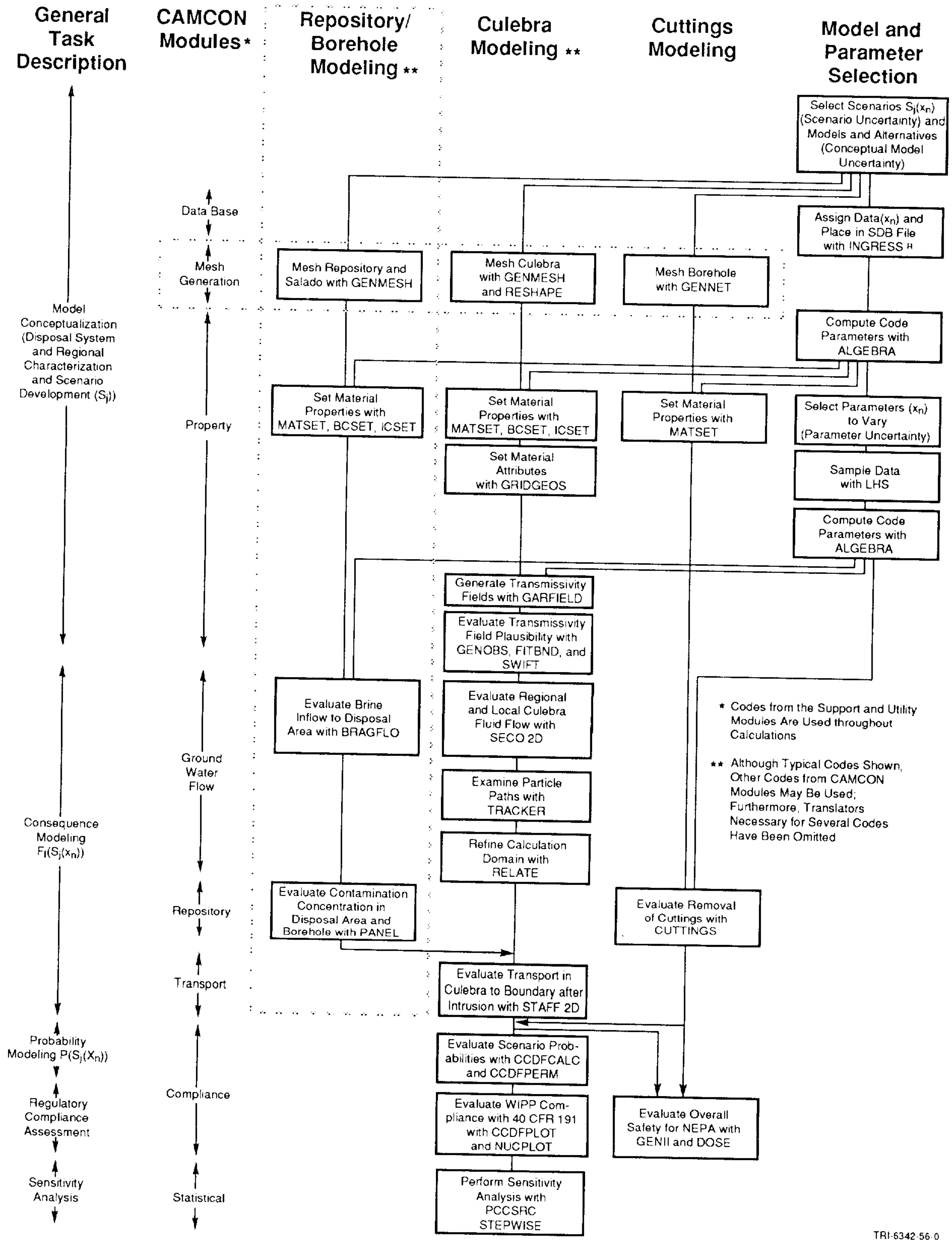


Figure 5-26. Organization of Programs in CAMCON (Rechard et al., 1989).

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON

Code	QA Status[1]	Work Remaining
Controller		
1. CAMCON	C	Notebook (listing); Review for Class A
Mesh Generation Module		
2. FASTQ: finite-element mesh generator	X	Add CAMDAT records
3. GENMESH: rectilinear mesh generator	A	Notebook
4. GENNET: network generator	C	Notebook; Review for Class A
5. PATEXO: PATRAN to CAMDAT transformation	X	Add CAMDAT records
Property Data Base Module		
6. GENPROP: item entry into property data base	C	Changes required by data base modification
7. INGRES™: relational data base	X	Helpfile; Notebook; Review for Class A
8. LISTSDB: data tabulation in secondary data base for reports	C	Make code more robust; SDB Reader; Update code; FLINT; Notebook
9. PLOTSDB: parameter distribution plots in secondary data base	C	SDB Reader; Document; Helpfile; FLINT; Notebook

QA Software Classifications:

1. A - Class A software has been evaluated by the Code Review Committee. The software satisfies the quality assurance requirements for traceability, retrievability, documentation, and verification. The software is available to any interested user within the WIPP Project at SNL.

   C - Class C software is a candidate for Class A, but currently satisfies only the traceability and retrievability requirements. The adequacy of documentation and verification has not been formally evaluated. An up-to-date Helpfile is maintained, a Software Abstract has been written, and internal documentation exists. However, both verification tests and external documentation are in progress. The software is available to any interested user within the WIPP Project at SNL.

   X - Class X software is currently being developed and has not been processed through any formal quality assurance procedures. The primary reason for the Class X classification is to make the existence of this software known to potential users. The software is available to any interested user within the WIPP Project at SNL.

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON (continued)

	Code	QA Status[1]	Work Remaining
Property Module			
10.	BCSET: boundary condition set up	C	Test cases; FLINT; Notebook; Review for Class A
11.	FITBND: fit of pressure optimization boundary conditions	X	Helpfile; [CAMCON]; Driver
12.	GARFIELD: attribute fields (e.g., transmissivity)	X	Helpfile; [CAMCON]; Driver; Test cases; FLINT; Notebook; Review for Class A
13.	GENOBS: functional relationships between well heads and pressure boundary conditions	X	Helpfile; [CAMCON]; Driver
14.	GRIDGEOS: interpolation from data to mesh	C	Check out kriging; Test cases; [CAMCON] FLINT; Notebook; Review for Class A
15.	ICSET: initial condition set up	C	Test cases; FLINT; Notebook; Review for Class A
16.	LHS: Monte Carlo sampling module	C	Test Cases; FLINT; Notebook; Review for Class A
17.	PRELHS: pre-LHS translator	C	FLINT; Notebook; Review for Class A
18.	POSTLHS: post-LHS translator	C	Algebraic function; FLINT; Notebook; Review for Class A
19.	MATSET: material property set up	C	Test cases; FLINT; Notebook; Review for Class A
20.	RELATE: interpolation from coarse to fine mesh and fine to coarse mesh (relates property and boundary conditions)	C	Document; Test cases; FLINT; Notebook; Review for Class A
21.	SORTLHS: vector reordering for LHS	X	Allow user to input own order; Test cases; FLINT; Notebook; Review for Class A
Groundwater Flow Module			
22.	BRAGFLO: 2-phase flow model	X	User manual

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON (continued)

	Code	QA Status[1]	Work Remaining
23.	PREBRAGFLO: pre-BRAGFLO translator	X	User manual
24.	POSTBRAGFLO: post-BRAGFLO translator	X	User manual
25.	BOAST_II: black oil model	X	Add semi-implicit wells; Add total velocity solution approach; Helpfile; [CAMCON]; FLINT; Test cases; Notebook; Review for Class A
26.	PREBOAST: pre-BOAST_II translator	C	(see BOAST_II, item 25)
27.	POSTBOAST: post-BOAST_II translator	C	(see BOAST_II, item 25)
28.	HST3D: hydrologic flow model	X	Add dynamic memory date and time; Add binary output
29.	PREHST: pre-HST3D translator	X	QA checkout
30.	POSTHST: post-HST3D translator	X	QA checkout
31.	SECO_2DH: 2-D hydrologic flow model, horizontal	X	Improve boundary condition capabilities; Use and Theory M; Test cases; Notebook; Review for Class A
32.	SUTRA: hydrologic flow model	C	CAMDAT source read; Test cases; Update; Helpfile; Notebook; Review for Class A
33.	PRESUTRA: pre-SUTRA translator	C	(see SUTRA, item 32)
34.	POSTSUTRA: post-SUTRA translator	C	(see SUTRA, item 32)
35.	SUTRA_GAS: SUTRA modification for fluid as gas instead of liquid	X	Helpfile; Notebook
36.	SWIFTII: hydrologic flow model	C	None at this time
37.	PRESWIFT: pre-SWIFTII translator	C	None at this time
38.	POSTSWIFT: post-SWIFTII translator	C	None at this time

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON (continued)

	Code	QA Status[1]	Work Remaining
Repository Module			
39.	CUTTINGS: evaluation of amount of material removed during drilling	C	Test cases; FLINT; Notebook; Review for Class A
40.	PANEL: panel model, mixing cell for radionuclides analytic flow modeling	X	Merge versions w and w/o brine pocket models; Test cases; Document; FLINT; Notebook; Review for Class A
Containment Transport Module			
41.	NEFTRAN: network transport model	C	None at this time
42.	PRENEF: pre-NEFTRAN translator	C	Changes required by modifications to CAMCON
43.	POSTNEF: post-NEFTRAN translator	C	None at this time
44.	STAFF2D: finite-element transport model	C	Check out multi-grid solver; Define permeability and porosity attributes; Test cases; FLINT; Notebook; Review for Class A
45.	PRESTAFF: pre-STAFF2D translator	C	(see STAFF2D, item 44)
46.	POSTSTAFF: post-STAFF2D translator	C	(see STAFF2D, item 44)
Compliance Module			
47.	CCDFCALC: CCDF calculation program	C	Test cases; Notebook; Review for Class A
48.	NUCPLOT: box plot of each radionuclide contribution to CCDF	C	Make more user friendly; Test cases; Notebook; Review for Class A
49.	CCDFPLOT: CCDF plotting	C	Notebook; Review for Class A
50.	GENII: human dose calculations	X	Document; Helpfile; [CAMCON]; Driver
51.	DOSE: dose calculations from transfer factors	X	Combine with PONDDOSE & FARMDOSE; Document; Helpfile; [CAMCON]; Driver

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON (continued)

	Code	QA Status[1]	Work Remaining
Support Module			
52.	ALGEBRA: CAMDAT manipulation program	C	Redo input structure; Examples; New manual; Notebook; Review for Class A
53.	BLOT: mesh and curve plotting	C	Add capability to plot geographical data; Element contours; Examples; New manual; Notebook; Review for Class A
54.	GROPE: CAMDAT file reader	C	Update helpfile; Notebook
55.	RESHAPE: redefinition of blocks (i.e., groupings of mesh elements)	C	Document; Test cases; FLINT; Notebook
56.	TRACKER: particle tracking support program	C	Add three-dimensional capability; Test cases; FLINT; Notebook; Review for Class A
57.	UNSWIFT: conversion of SWIFT input files into CAMDAT	C	Notebook
Statistical Module			
58.	PCCSRC: partial correlation coefficient statistics	C	Test cases; Notebook; Review for Class A
59.	STEPWISE: stepwise statistics	C	Document; Test cases; Notebook; Review for Class A
60.	LHS2STEP: translator from from LHS to STEPWISE or PCC/SRC	C	(see STEPWISE, item 59)
61.	CCD2STEP: translator from CCDFCALC	C	(see STEPWISE, item 59)
Utilities			
62.	CAM2TXT: binary CAMDAT to ASCII conversion	X	None at this time
63.	CHAIN: radionuclide chains	X	[CAMCON]; Notebook
64.	CHANGES: record of needed enhancements to CAMCON or codes	C	None at this time

TABLE 5-1. SEPTEMBER 1991 STATUS OF COMPOSITE PROGRAMS IN CAMCON (continued)

	Code	QA Status[1]	Work Remaining
65.	DISTRPLT: pdf's plots given parameters	X	[CAMCON]; Helpfile; Notebook
66.	FLINT: FORTRAN language analyzer	X	[CAMCON]; Helpfile
67.	HLP2ABS: conversion of helpfile to software abstract	X	Switch over from R:BASE™ to INGRES™; [CAMCON]; Helpfile
68.	LISTDCL: list of DEC command procedural files	C	None at this time
69.	LISTFOR: list of programs & sub-routines; summary of comments & active FORTRAN lines	C	None at this time
70.	NEFDIS: plot of NEFTRAN discharge history as a function of time	X	[CAMCON]
71.	SCANCAMDAT: quick summary of data in CAMDAT	X	Helpfile; Notebook
72.	TXT2CAM: ASCII to binary CAMDAT conversion	X	None at this time
Libraries			
73.	CAMCON_LIB	X	Architecture manual; Helpfile; Notebook; Review for Class A
74.	CAMSUPES	X	Add PARSE; Architecture manual; Helpfile; Notebook
75.	DVDI	X	Architecture manual; Helpfile; Notebook; Review for Class A
76.	PLOTLIB	X	Architecture manual; Helpfile; Notebook Review for Class A
77.	PLT	X	Architecture manual; Helpfile; Notebook; Review for Class A
78.	SDBREAD	X	Architecture manual; [CAMCON]; Helpfile; Notebook; Review for Class A
79.	CDBREAD	X	Under development

Chapter 5–Synopsis

The physical components of the disposal system and its surroundings provide barriers to radionuclide migration during the 10,000 years of regulatory concern.

The Natural Barrier System

Castile Formation

The Castile Formation (Late Permian), located immediately below the rock unit containing the repository, consists mostly of anhydrite and at some locations contains reservoirs of pressurized brine.

Pressurized brine in the Castile Formation could reach the repository through an intrusion borehole.

Salado Formation

The Salado Formation (Late Permian), the host rock for the repository, is about 600 m (1970 ft) thick at the WIPP and is mostly halite with some anhydrite interbeds.

Where the Salado Formation is intact and unaffected by dissolution, circulation of groundwater is extremely slow because primary porosity and open fractures are lacking.

Rustler Formation

The Rustler Formation (Late Permian), above the Salado Formation, contains five members. Two of these members, the Culebra and Magenta Dolomite Members, are considered in performance assessments because they are potential pathways for release of radionuclides to the accessible environment.

Climate

The present climate of southeastern New Mexico is arid to semi-arid. Geologic data show past alternations of wetter and drier climates that correspond to global cycles of glaciation and deglaciation.

Mean annual precipitation at the last glacial maxima was approximately twice that of the present.

Climatic variability is incorporated into the modeling system by varying boundary conditions of the two-dimensional, groundwater-flow model for the Culebra Dolomite Member of the Rustler Formation.

Surface Water

The principal surface-water feature in southeastern New Mexico is the Pecos River, which is about 20 km (12 mi) southwest of the WIPP at its closest point.

Several shallow, saline lakes in Nash Draw 8 km (5 mi) west of the WIPP collect precipitation, surface drainage, and groundwater discharge from springs and seeps.

The Water Table

Away from the immediate vicinity of the Pecos River, near-surface rocks are either unsaturated or of low permeability and do not produce water in wells.

Regionally, water-table conditions can be inferred for the more permeable units where they are close to the surface and saturated.

Regional Water Balance

Water inflow to the area comes from precipitation, surface-water flow in the Pecos River, groundwater flow across the boundaries of the region, and water imported to the region for human use.

Outflow from the water-budget model occurs as stream-water flow in the Pecos River, groundwater flow, and evapotranspiration.

Immediately around the WIPP, where no surface runoff occurs and all precipitation not lost to evapotranspiration must recharge groundwater, evapotranspiration may be as high as 98-99.5%.

Groundwater Flow above the Salado Formation

Although preliminary hydrologic modeling indicates the possibility of some vertical flow between hydrostratigraphic units, for the 1991 performance-assessment calculations units are assumed to be perfectly confined.

Potentiometric maps show differences in flow directions and indicate slow flow rates between the three major hydrostratigraphic units: they do not function as a single aquifer.

Groundwater Geochemistry

Groundwater quality of the Rustler-Salado contact residuum and the Culebra and Magenta Dolomite Members is poor, with total dissolved solids exceeding 10,000 mg/ℓ (the level set for regulation by the Individual Protection Requirements of the Standard) in most locations.

Recharge and Discharge

Potentiometric-surface mapping indicates that recharge to the Culebra Dolomite may be in an area north of the WIPP where the Rustler crops out, and through leakage from overlying units.

Discharge from the Culebra Dolomite is indicated toward the south, possibly into the Rustler-Salado contact residuum under water-table conditions near Malaga Bend and ultimately into the Pecos River. The Culebra may also discharge directly into the Pecos River or into alluvium.

Recharge to the Magenta Dolomite may also occur in an area north of the WIPP.

Discharge near the WIPP from the Magenta Dolomite is indicated toward the west, probably into the Tamarisk Member and the Culebra Dolomite near Nash Draw. Additional discharge may ultimately reach the saline lakes in Nash Draw, the Pecos River at Malaga Bend, or the alluvium in the Balmorhea-Loving Trough.

Groundwater Flow and Transport Models for the Culebra Dolomite

The Culebra Dolomite is modeled for performance assessment as a perfectly confined, two-dimensional aquifer.

Darcy flow is calculated for a single phase (liquid), and radionuclide transport is assumed to occur in a dual-porosity (fractures and matrix) medium.

The performance-assessment model allows for retardation during transport both by diffusion and sorption in matrix porosity and sorption by clays that line fractures. Retardation factors used in the 1991 preliminary comparison are based on expert judgment elicited from a panel of SNL researchers.

The Engineered Barrier System

Currently, engineered barriers in the WIPP are seals in panels, drifts, and shafts.

Other possible engineered barriers are modifications to the form of the waste and backfill or to the design of the waste-disposal areas.

The Salado Formation at the Repository Horizon

The repository has been excavated within a single stratigraphic horizon in the salt so that all panels within the waste-disposal area share the same local stratigraphy.

Excavation of the repository and the consequent release of lithostatic stresses have created a disturbed rock zone (DRZ) around the underground openings. Fracturing in the DRZ may provide a pathway for fluid migration out of the repository and possibly around panel and drift seals.

Repository and Seal Design

Waste will be emplaced within panels in drums or metal boxes, and panels will be backfilled and sealed as they are filled.

Backfill will reduce initial void space and permeability in the panels and will consolidate under pressure to further limit brine flow through the waste. Pure crushed salt, which will not sorb radionuclides, is currently assumed as backfill material.

The primary long-term component of the seals will be crushed salt, confined between short-term rigid bulkheads that will prevent fluid flow while creep closure reconsolidates the crushed salt to properties comparable to those of the intact Salado Formation.

Waste Characterization

The Waste Acceptance Certification requirements state that waste must be immobilized if it contains particulates in specified ranges. Waste must also be drained of liquids and contain no explosives or compressed gases.

Waste is characterized for the 1991 calculations by scaling 1987 data up to the design capacity of the repository. Estimates are made of the amounts of combustibles, metals, and other constituents of the waste.

The Radionuclide Inventory

Current performance-assessment calculations use an initial waste inventory that includes both CH and RH waste that currently exists or is estimated to be generated by 2013, based on 1990 data scaled up to the design volume of the repository.

The radionuclide inventory for transport calculations is a function of the initial inventory and decay within the repository before transport begins.

Radionuclide Solubility and the Source Term for Transport Calculations

Radionuclide solubility limits for the 1991 preliminary comparison are based on judgment elicited from an expert panel. Concentrations of suspended materials are not considered.

Performance-Assessment Model for the Repository/Shaft System

Liquid and gas flow in the Salado Formation is simulated as a function of the various processes active in the waste-disposal panels, including borehole intrusion.

All of the major processes active in the waste-disposal area are linked, and all are rate- and time-dependent.

Time and rate of gas generation will strongly influence repository pressurization and closure. Gas-generation rates will be dependent on specific reaction rates and the availability of reactants.

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

Modeling of Undisturbed Performance

Because estimates of undisturbed performance indicate no releases to the accessible environment, simulations of undisturbed performance are not included in the probabilistic calculations used to generate the CCDF curves.

For the 1991 preliminary comparison, the programs SUTRA and STAFF2D are used with two two-dimensional repository models (a horizontal and a vertical section through the system) to estimate radionuclide migration away from the undisturbed repository. Gas-pressurization effects are included by using elevated repository pressures calculated using the two-phase flow program BOAST_II.

Modeling of Disturbed Performance

The transient two-phase flow program BRAGFLO calculates brine and gas flow within waste panel, the surrounding rock, and an intrusion borehole. Gas-generation reactions are calculated dependent on availability of reactants (metal and cellulose) and brine saturation.

The program PANEL calculates radionuclide concentrations in repository brine as a function of solubility and decay.

Modeling of Radionuclide Releases during a Borehole Intrusion

The program CUTTINGS is used to estimate the quantity of cuttings and cavings from the drilling process released to the accessible environment in a settling pit at the surface.

CAMCON: Controller for Compliance Assessment System

The Compliance Assessment Methodology CONtroller (CAMCON) controls code linkage and data flow during lengthy and iterative consequence analyses, minimizes analyst intervention during data transfer, and automatically handles quality assurance during calculations.

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6. CONTAINMENT REQUIREMENTS

[NOTE: The text of Chapter 6 is followed by a synopsis that summarizes essential information, beginning on page 6-17.]

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 according to Table 1 (Appendix A [of the Standard]); 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 [of the Standard]). (§ 191.13(a))

As indicated in Chapters 2 and 3 of this volume, compliance with the Containment Requirements will be evaluated using a family of CCDF curves that graph exceedance probability versus cumulative radionuclide releases for all significant scenarios. As discussed further in Chapters 10 and 11 of this volume, 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 not included, 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 data base.

Results in the form of CCDFs for the 1991 preliminary compliance assessment are presented separately for total releases (cuttings/cavings plus subsurface) to the accessible environment and for subsurface groundwater releases only. These CCDF presentations are the culmination of the application of the conceptual model for risk (performance assessment) described in Chapter 3 of this volume.

6.1 Conceptual Model for Risk

Construction of CCDFs presented in this chapter is based on the conceptual representation of performance assessment described in Chapter 3 of this volume. The outcome of the performance assessment is represented as a set of ordered triples of the form

$$R = \{(S_i,\ pS_i,\ \mathbf{cS}_i),\ i=1,\ \ldots,\ nS\} \qquad (6\text{-}1)$$

where

S_i = a set of similar occurrences,

pS_i = probability that an occurrence in the 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).

In terms of performance assessment, the S_i are scenarios, the pS_i are scenario probabilities, and the $\mathbf{cS}_i$ are vectors containing results or consequences associated with scenarios. The information contained in the pS_i and $\mathbf{cS}_i$ is summarized in the form of CCDFs as exceedance probability versus consequence curves. The construction of these curves is described in Volume 2, Chapter 3 of this report.

6.2 Scenarios Included and Probability Estimates

The representation of the performance assessment as an ordered triple involves scenario probabilities that require an underlying sample space. The introduction to Chapter 4 of this volume defined this sample space, S, as

$$S = \{x\text{: x is a single 10,000-year history beginning at decommissioning}\}. \qquad (6\text{-}2)$$

Following the screening of a comprehensive list (Table 4-1) of possible events and processes that could affect future states of the waste-barrier system, a logic diagram (Figure 4-5) was used to construct summary scenarios, S_i, that are mutually exclusive sets of common occurrences whose union is S, i.e.,

$$S = \bigcup_{i=1}^{8} S_i \ . \tag{6-3}$$

The base-case summary scenario, S_1, in the logic diagram is the undisturbed scenario for the Containment Requirements. Since there are no releases estimated to occur in the 10,000-year regulatory period (Volume 2, Chapter 4 of this report), S_1 is not analyzed, but it is included in CCDF construction through its estimated probability and zero consequences (Figure 4-2). In order to display the family of CCDFs such that stochastic variability and uncertainty due to imprecisely known variables are clearly separated, the summary scenarios, S_i, for human intrusion are further refined into computational scenarios denoted $S(\mathbf{n})$, $S(\mathbf{l},\mathbf{n})$, $S^{+-}(t_{i-1}, t_i)$, and $S^{+-}(\mathbf{l};t_{i-1}, t_i)$, which are disjoint sets of common occurrences defined such that it is reasonable to use the same consequences for all elements of each computational scenario and such that consequences can be estimated with reasonable computational cost.

The factors used to define $S(\mathbf{n})$, $S(\mathbf{l},\mathbf{n})$, $S^{+-}(t_{i-1}, t_i)$, and $S^{+-}(\mathbf{l};t_{i-1}, t_i)$, are: number and time of intrusions (Volume 2, Chapter 2, Tables 2-2 and 2-3), flow through a panel due to penetration of a pressurized brine reservoir in the Castile Formation (Volume 2, Chapter 2, Table 2-6), and activity level of the waste penetrated by a borehole (Volume 2, Chapter 2, Table 2-7). These factors all relate to stochastic or Type A uncertainty since they lead to values used for pS_i in constructing the CCDFs.

For the 1991 performance assessment, drilling intrusions are assumed to follow a Poisson process (i.e., intrusions occur randomly in space and time with a fixed rate constant). The rate constant is an imprecisely known variable with upper bound defined by the regulatory guidance of 30 boreholes/km^2/10,000 yr and lower bound of zero. The Poisson rate constant is assumed to be a uniformly distributed variable and is included in the set of imprecisely known variables that accounts for Type B uncertainty. Since the EPA limit requires estimation of cumulative probability through the 0.999 level, consequences of computational scenarios involving up to 10 or 12 drilling intrusions may be included in the comparison with regulatory limits. For this performance assessment, the regulatory time interval of 10,000 years is divided into five disjoint time intervals of 2,000 years each with intrusion occurring at the midpoints of these intervals (i.e., 1000, 3000, 5000, 7000, and 9000 years).

For the 1991 performance assessment, the waste panels are assumed to be underlain by one or more pressurized brine reservoirs in the Castile Formation. The possible location of these brine reservoirs is shown in Volume 3. The fraction of waste panel area underlain by brine reservoirs is included in the set of imprecisely known variables. The uncertainty in this parameter is Type B (i.e., subjective), although the parameter itself is used in the calculation of the probabilities pS_i that characterize Type A (i.e., stochastic) uncertainty.

For the 1991 performance assessment, activity loading of the waste within a panel is included. Four CH activity levels and one RH activity level are defined to represent variability in the activity level of waste penetrated by a drilling intrusion. The distribution of activity levels for existing waste to be shipped to the WIPP is contained in Volume 3 of this report. This distribution was scaled up from existing waste to the WIPP design capacity for the 1991 performance assessment. As with the rate constant λ in the model for the occurrence of drilling intrusions and the area fraction for pressurized brine, the distribution of activity loading is used in the calculation of the probabilities pS_i.

The three factors just listed (Poisson rate constant, area of brine reservoir, and variable activity loading) are used in probability models (Volume 2, Chapter 2 of this report) for estimating computational scenario probabilities, pS_i. These estimates determine the vertical step sizes of the CCDFs and therefore represent Type A or stochastic uncertainty. The probabilities used in this performance assessment are not always exact for a Poisson process because some assumptions are made to simplify the calculations. However, these assumptions are made so that probability estimates are bounding, i.e., estimates used are greater than an exact calculation (i.e., $p(\cup_i S_i) = \Sigma_i pS_i$) to simplify calculations for some S_i.

In developing the logic diagram for defining summary scenarios and setting up the design of the consequence modeling a number of additional assumptions have been made. These are summarized in Table 6-1.

Previous calculations (Marietta et al., 1989; Bertram-Howery et al., 1990) have analyzed summary scenarios, S_1, S_2, S_3, and S_4 in Figure 4-5. CCDFs were constructed as described by Cranwell et al. (1990) using fixed scenario probabilities. CCDFs presented in this report do not use the same construction technique but follow the procedure described in Volume 2, Chapter 3 of this report. Scenario probabilities are not fixed. Instead, probabilities are calculated for computational scenarios $S(\mathbf{n})$, $S(\mathbf{l},\mathbf{n})$, $S^{+-}(t_{i-1}, t_i)$, and $S^{+-}(\mathbf{l};t_{i-1}, t_i)$ as described in Chapter 4 of this volume, using the probability models defined in Volume 2, Chapter 2 of this report.

TABLE 6-1. ASSUMPTIONS USED TO DEFINE COMPUTATIONAL SCENARIOS FOR RESULTS REPORTED IN THIS CHAPTER

1. No connections exist between panels.
2. No synergistic effects result from multiple boreholes except for $E1E2$-type computational scenarios.
3. An $E1E2$-type computational scenario only occurs when intrusions of each type happen in the same panel within the same time interval.
4. An $E1E2$-type computational scenario has the same release with more than two intrusions in one panel as with exactly two intrusions.
5. In an $E2$-type computational scenario, a plug exists directly above the Culebra Unit in the Rustler Formation that directs flow into the Culebra, and this plug is effective for 10,000 years following decommissioning.
6. In an $E1$-type computational scenario, a plug exists as in number five, and no other plug exists to retard flow from the Castile pressurized brine reservoir.
7. In an $E1E2$-type computational scenario, number five is true for one intrusion, and a similar plug exists between the repository and the Rustler Formation that directs flow through the penetrated waste panel toward the other intrusion in the same panel. Further, both intrusions are conservatively assumed to occur at the same time.
8. Computational scenarios involving subsidence events are not included in this performance assessment, which is equivalent to assuming that subsidence has no effect on the consequences calculated for the scenarios under consideration.
9. Closure of the intrusion boreholes is not included in this performance assessment.

Fundamental differences between this year's and previous years' performance assessments are the refinement of summary scenarios into computational scenarios and the use of the Poisson assumption of random intrusion in space and time for calculating scenario probabilities. The CCDF construction procedure used for this year's performance assessment results in an explicit representation for the effects of stochastic variability (Type A uncertainty).

6.3 Imprecisely Known Parameters

Forty-five imprecisely known parameters were sampled for use in consequence modeling for the Monte Carlo simulations of performance. For each of these 45 parameters, a range and distribution were assigned as discussed in Volume 3 of this report. However, Volume 3 lists approximately 300 parameters that could be used in consequence modeling. These parameters specify physical, chemical, and hydrologic properties of the rock formations (geologic barriers) and of the seals, backfill, and waste form (engineered barriers). Parameters for climate variability and future drilling intrusions are included in this list. Selection of the set of parameters to be sampled is an important decision in designing each year's preliminary compliance assessment. The present study is preliminary, so the final set of sampled parameters will probably differ from the present set. Table 6-2 lists the set of imprecisely known parameters that was sampled for the 1991

TABLE 6-2. LIST OF PARAMETERS SAMPLED FOR THE 1991 PRELIMINARY COMPARISON

Parameter Name	Volume 3 Reference
Salado Formation	
1. Far-field pore pressure	2.4.6
2. Anhydrite permeability/undisturbed	2.4.5
3. Anhydrite porosity/undisturbed	2.4.7
4. Threshold pressure/anhydrite	2.4.1
5. Halite permeability/undisturbed	2.3.5
Castile Formation	
6. Initial pressure/brine reservoir	4.3.2
7. Bulk storativity/brine reservoir	4.3.2
Rustler Formation/Culebra Dolomite Member	
8. Longitudinal dispersivity	2.6.2
9. Fracture spacing	2.6.4
10. Fracture porosity	2.6.4
11. Matrix porosity	2.6.4
12. Transmissivity conditional simulations[1]	V.2, Sec. 6.3
Partition coefficients/fracture	2.6.10
13. Am	
14. Np	
15. Pu	
16. Th	
17. U	
Partition coefficients/matrix	2.6.10
18. Am	
19. Np	
20. Pu	
21. Th	
22. U	
As-Received Waste Form	
Gas generation/corrosion	3.3.8
23. Inundated generation rate	
24. Humid generation rate[2]	
25. Stoichiometry	
Gas generation rate/biodegradation	3.3.9
26. Inundated generation rate	
27. Humid generation rate[2]	
28. Stoichiometry	

1. A sample is drawn from a uniform variate over a set of 60 fields for transmissivity, each assumed to have equal probability, and each conditioned on transmissivity measurements at well locations and pilot point values.

2. Humid generation rates are relative to inundated rates such that the upper bound for the humid rate is always the value sampled for the inundated rate for each sample element.

TABLE 6-2. LIST OF PARAMETERS SAMPLED FOR THE 1991 PRELIMINARY COMPARISON (concluded)

Parameter Name	Volume 3 Reference
Dissolved concentrations/solubility[3]	3.3.5
29. Am^{3+}	
30. Np^{4+}	
31. Np^{5+}	
32. Pu^{4+}	
33. Pu^{5+}	
34. Th^{4+}	
35. U^{4+}	
36. U^{5+}	
Volume fractions of IDB categories	3.4.1
37. Metal/glass	
38. Combustibles	
39. Initial waste saturation	3.4.9
40. Eh-pH conditions	3.3.6
Agents Acting on Disposal System	
Human intrusion borehole	
41. Borehole-fill permeability	4.2.1
42. Borehole diameter	4.2.2
43. Climate/recharge factor	4.4.3
Probability Model for Computational Scenarios	
44. Area fraction of pressurized brine reservoir/Castile	5.1.1
45. Rate constant for Poisson drilling model	5.2.1

3. Each pair, (Np^{4+},Np^{5+}), (Pu^{4+},Pu^{5+}), and (U^{4+},U^{5+}), is correlated at a level of 0.99.

performance assessment. Included are the names and a reference to Volume 3 of this report for each parameter. A summary table of these parameters with a range, median, distribution, and original reference for each is given in Volume 3, Chapter 6 of this report.

Fundamental differences from last year's preliminary comparison are the addition of parameters related to two-phase flow and gas generation, parameters related to dual porosity (both chemical and physical retardation) in the Culebra, and a set of conditional simulations for transmissivity in the Culebra instead of the 1990 simple zonal approach. The 1991 calculations also include a preliminary analysis of potential effects of climatic variability on flow in the Culebra.

6.4 Sample Generation

Latin hypercube sampling is used to incorporate Type B uncertainty (i.e., uncertainty due to imprecisely known variables) into the performance assessment (Chapter 3 of this volume). Specifically, a Latin hypercube sample of size 60 was generated from the set of 45 variables listed in Table 6-2. Restricted pairing was used to prevent any spurious correlations. The resultant sample is listed in Volume 2, Appendix B of this report.

Decomposition of the sample space S into the computational scenarios described above is a form of stratified sampling (Chapter 3 of this volume), where the pS_i are the strata probabilities. This stratified sampling incorporates Type A or stochastic uncertainty into the performance assessment and forces the inclusion of low-probability, high-consequence computational scenarios (e.g., $E1E2$-type drilling intrusions).

6.5 Consequence Modeling

After the sample is generated, each element of the sample is propagated through the system of codes used for scenario analysis. Only human-intrusion computational scenarios are included. In the 1991 performance assessment, the major modules used to simulate flow and transport are CUTTINGS, BRAGFLO, PANEL, SECO2D, and STAFF2D. These codes are linked and the data flow controlled by the CAMCON executive package (Rechard et al., 1989). Each sample was used in the calculation of both cuttings/cavings and subsurface groundwater releases for intrusion times of 1000, 3000, 5000, 7000, and 9000 years for $E2$- and $E1E2$-type intrusions. Consequences, $\mathbf{cS}_i$, of $E1$-type intrusions were found to be similar to and bounded by $E1E2$-type intrusions, so only the latter required calculations. Therefore, 600 executions of the linked system of codes were needed to generate the required set of consequences for subsurface groundwater releases. The resulting set of consequences (cuttings/cavings plus subsurface groundwater releases) were used by the probability model, CCDFPERM, to calculate a family of CCDFs and its summary curves (median, mean, and various quantiles). The probability model calculates probabilities and consequences for computational scenarios for all combinations of the activity levels and time intervals, resulting in up to 800,000 computational scenarios included in this performance assessment.

The important assumptions for the 1991 preliminary comparison are listed in Table 6-3.

TABLE 6-3. PARTIAL LIST OF ASSUMPTIONS MADE IN CONSEQUENCE MODELING FOR RESULTS REPORTED IN THIS CHAPTER

Compliance-Assessment System Component	Assumption	Cross-Reference
REPOSITORY/SHAFT/ BOREHOLE MODELS: REPOSITORY/SHAFT DESIGN		
Panel, Drift and Lower Shaft Seals	Reconsolidate to properties close to those of intact salt	V.3,Ch.3
	No MB139 or anhydrite A and B seals	V.2,Ch.5
REPOSITORY/SHAFT/ BOREHOLE MODELS: PANEL MODEL		
Salado Formation	Homogeneous time-invariant material properties within each stratigraphic unit	V.2, Ch.5; V.3, Ch.2
	Initial brine saturation in Salado	V.2, Ch.5
Waste/Backfill	Homogeneous material properties and time-invariant porosity on a panel scale	V.2, Ch.5; V.3, Ch.3
	No sorptive retardation in backfill	V.1, Ch.5
	CH waste emplaced only in 55 gal drums and standard waste boxes	V.3, Ch.3
	IDB radionuclide inventory extrapolated to design capacity	V.1,Ch.5; V.3, Ch.3
	Volume fractions of combustibles and metals/glass extrapolated to design capacity	V.3, Ch.3
	All combustibles and 50% of rubbers biodegrade	V.3, Ch.3
	RH waste included in cuttings but not subsurface groundwater releases	V.2, Ch.2,7
	Activity loading variability included for CH waste	V.2, Ch.2
	No radionuclide transport as colloids	V.1, Ch.5; V.3, Ch.3
Panel/Waste Interactions	Panel modeled with equivalent-enclosed-volume cylindrical geometry	V.2, Ch.5

TABLE 6-3. PARTIAL LIST OF ASSUMPTIONS MADE IN CONSEQUENCE MODELING FOR RESULTS REPORTED IN THIS CHAPTER (continued)

Compliance-Assessment System Component	Assumption	Cross-Reference
	Gas generated by corrosion and biodegradation only (no radiolysis)	V.2, Ch.5 V.3, Ch.3
	Gas generation proportional to brine saturation	V.2, Ch.5
	Brine consumed during corrosion; no gas consumed within the panel	V.2, Ch.5
	Fracture flow limited to MB139/room interaction	V.3, Ch.3
	Brine and gas flow obeys generalized Darcy's Law for compressible fluids in all media	V.2, Ch.5
	No dissolved gas in brine phase	V.2, Ch.5
	Solubility limits allocated among isotopes of an element based on relative abundance	V.2, Ch.5
	Radionuclide concentrations assumed to be uniform throughout panel and in equilibrium at all times	V.2, Ch.5
Human Intrusion (see Table 6.1)	Exploratory hydrocarbon drilling only	V.1, Ch.4
	Future drilling technology comparable to present	V.1, Ch.4,5; V.3, Ch. 7
	Arbitrary plug configurations for scenarios	V.1, Ch.4
	Brine reservoirs in the Castile Fm. underlie portions of some waste panels	V.1, Ch.4; V.2, Ch.2
	Some plugs deteriorate, some remain intact from time of emplacement through remainder of 10,000 years	V.1, Ch.4; V.3, Ch.4
	Probability of intrusion follows a Poisson process (i.e., random in space and time for 9900 years)	V.1, Ch.4; V.2, Ch.2; V.3, Ch.5
	Borehole-fill properties comparable to silty sand	V.3, Ch.4
	Source for all intrusion boreholes for Culebra transport located above center of waste-disposal area	V.2, Ch.6

TABLE 6-3. PARTIAL LIST OF ASSUMPTIONS MADE IN CONSEQUENCE MODELING FOR RESULTS REPORTED IN THIS CHAPTER (continued)

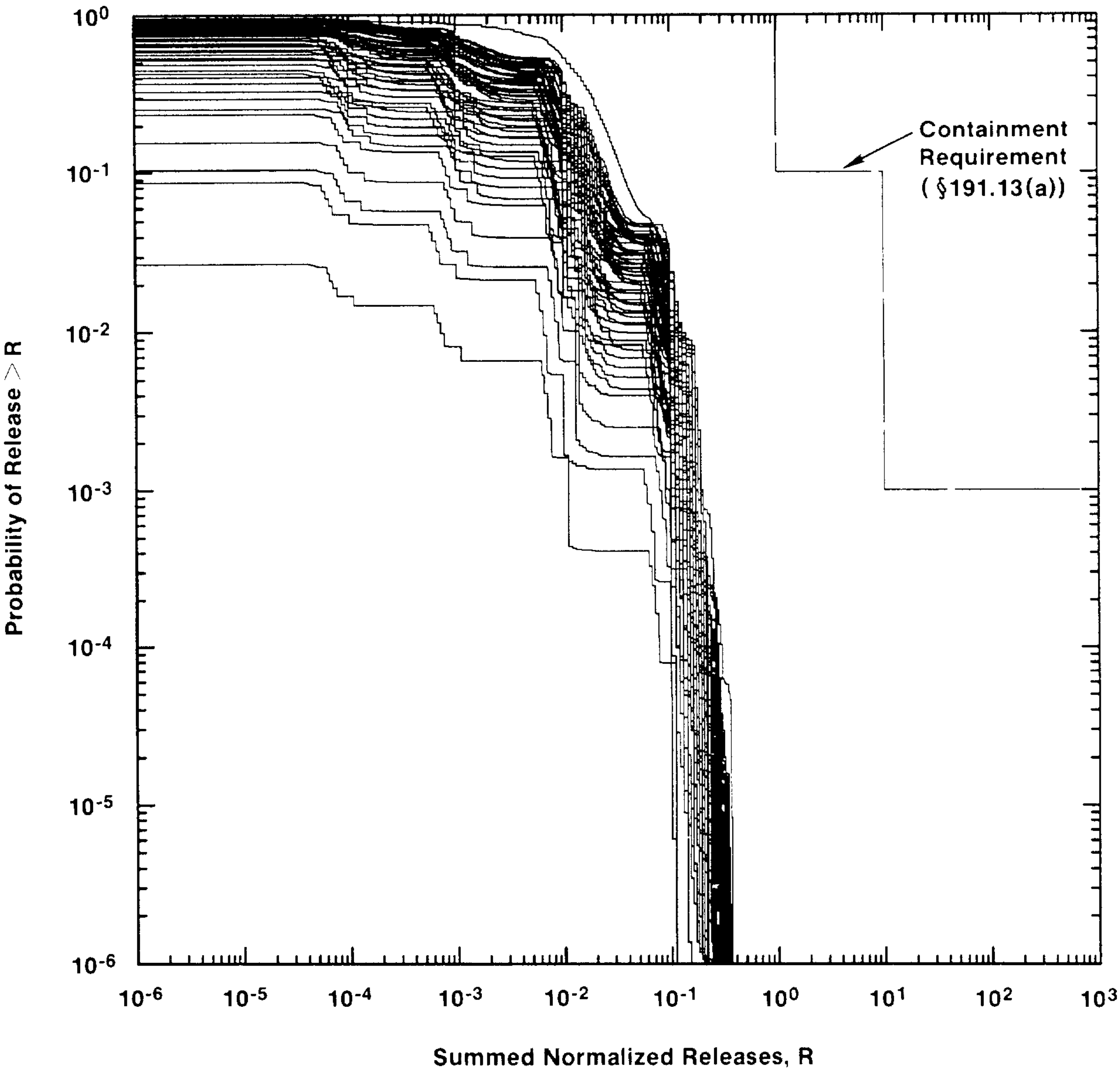
Compliance-Assessment System Component	Assumption	Cross-Reference
REPOSITORY/SHAFT MODELS: REPOSITORY MODEL		
Panel and Drift Seals	Reconsolidate to properties close to those of intact salt	V.3, Ch.3
Lower Shaft Seals	Reconsolidate to properties close to those of intact salt	V.3, Ch.3
GROUNDWATER-FLOW AND TRANSPORT MODELS: GROUNDWATER-FLOW MODEL		
Regional Hydrogeology	Rock properties are time invariant	V.1, Ch.4, 5
	Future climate variability bounded by past	V.1, Ch. 5
Rustler/Dewey Lake Hydrogeology	2-D, confined,single porosity, Darcy flow model for Culebra	V.1, Ch. 5 V.2, Ch.6
	60 transmissivity fields conditioned on measured transmissivities at well locations and pilot point values represent uncertainty in field	V.2, Ch.6
	Changes in recharge restricted to northern boundary	V.1, Ch.5 V.2, Ch.6
	No flow boundary along Nash Draw, constant heads on other boundaries except for recharge strip	V.2, Ch.6
	Impact of subsidence not considered	V.2, Ch.6
	Future vertical flow through existing boreholes not considered	V.2, Ch.6
	Variable-density effects not considered	V.2, Ch.6
	Brine flow from intrusion borehole does not alter flow in Culebra	V.2, Ch.6
GROUNDWATER FLOW AND TRANSPORT MODELS: RADIONUCLIDE TRANSPORT MODEL		
Physical Retardation	Dual-porosity medium for transport	V.1, Ch.5; V.2, Ch.6

TABLE 6-3. PARTIAL LIST OF ASSUMPTIONS MADE IN CONSEQUENCE MODELING FOR RESULTS REPORTED IN THIS CHAPTER (concluded)

Compliance-Assessment System Component	Assumption	Cross-Reference
Chemical Retardation	Retardation in both clay-lined fractures and dolomite matrix	V.1, Ch.5; V.2, Ch.6
	Transport by colloids not considered	V.1, Ch.5; V.2, Ch.6
CUTTINGS/CAVINGS MODEL		
Drill Cuttings	Homogeneous waste properties	V.1, Ch.5; V.2, Ch.7
	Present-day rotary drilling methods	V.1, Ch.5; V.2, Ch.7
Erosion/Cavings	Spalling from gas-filled waste panel not considered	V.1, Ch.5; V.2, Ch.7
	Waste characterized by an effective shear strength	V.1, Ch.5; V.2, Ch.7
	Erosion occurs when drilling fluid shear stress exceeds effective shear strength	V.1, Ch.5; V.2, Ch.7

6.6 1991 Performance Assessment CCDFs

The CCDFs resulting from the 1991 analysis described above are displayed in Figures 6-1 and 6-2. Figure 6-1 is the family of CCDFs for total release (cuttings/cavings plus subsurface groundwater) to the accessible environment. Figure 6-2 is a set of summary curves (median, mean, and two quantiles) derived from this family. To illustrate the effect of cuttings and cavings, subsurface groundwater releases are displayed separately in Figures 6-3 and 6-4. Except for a few low-probability releases, cuttings and cavings dominate the CCDFs for total releases. Based on the performance-assessment data base and present understanding of the WIPP disposal system, the summary curves in Figure 6-2 are considered to be the most realistic choice for preliminary comparison with the Containment Requirements of EPA *40 CFR 191*. Additional CCDFs are presented with sensitivity analysis results and alternate displays of uncertainty analysis results in Volume 4 of this report.



TRI-6342-1293-0

Figure 6-1. Family of CCDFs Showing Total Cumulative Normalized Releases to the Accessible Environment Resulting from Both Groundwater Transport in the Subsurface and Releases at the Surface during Drilling. CCDFs are conditional on assumed scenarios, models, and distributions for parameter values, as described in the text and in Volumes 2 and 3 of this report.

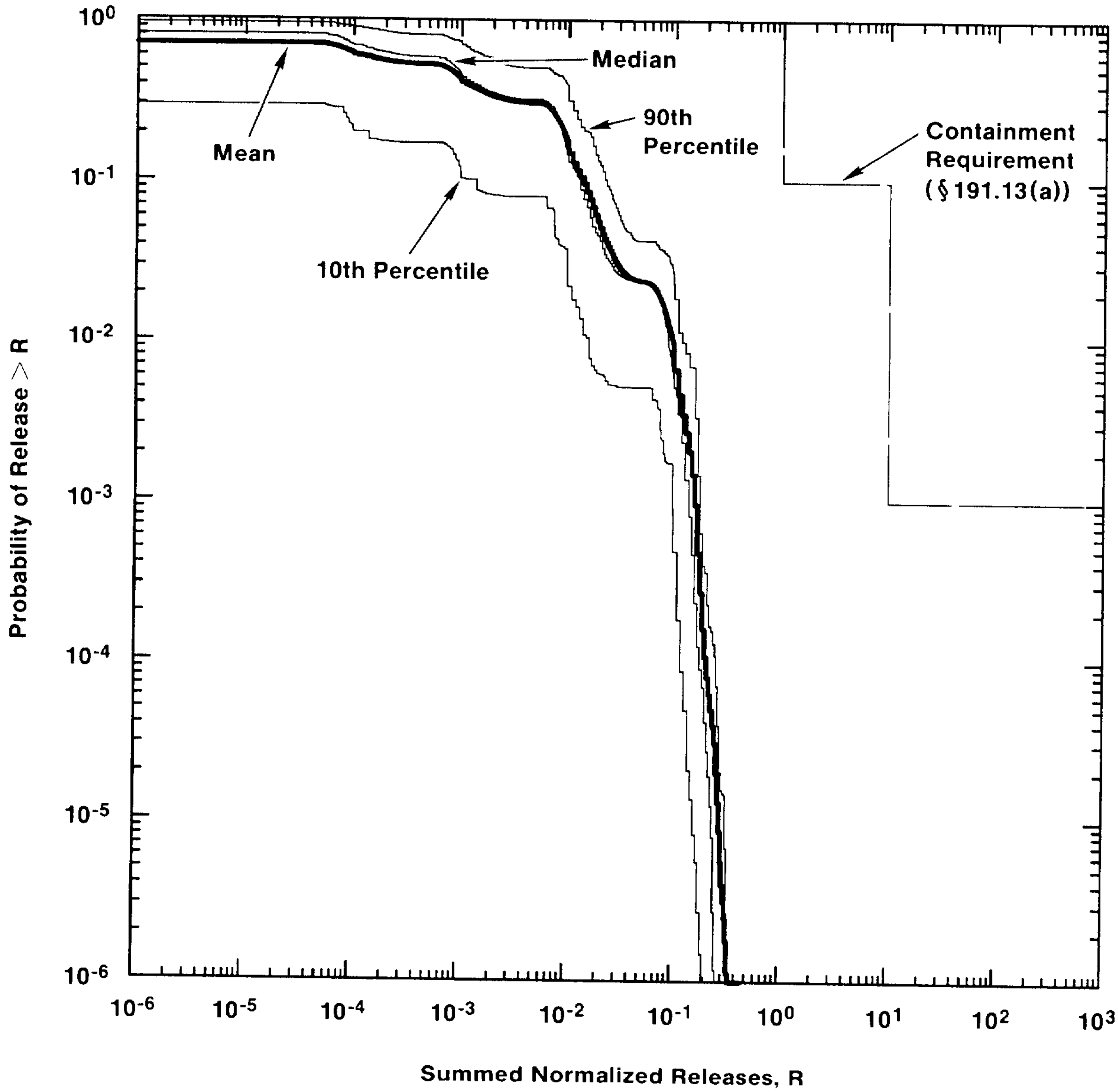
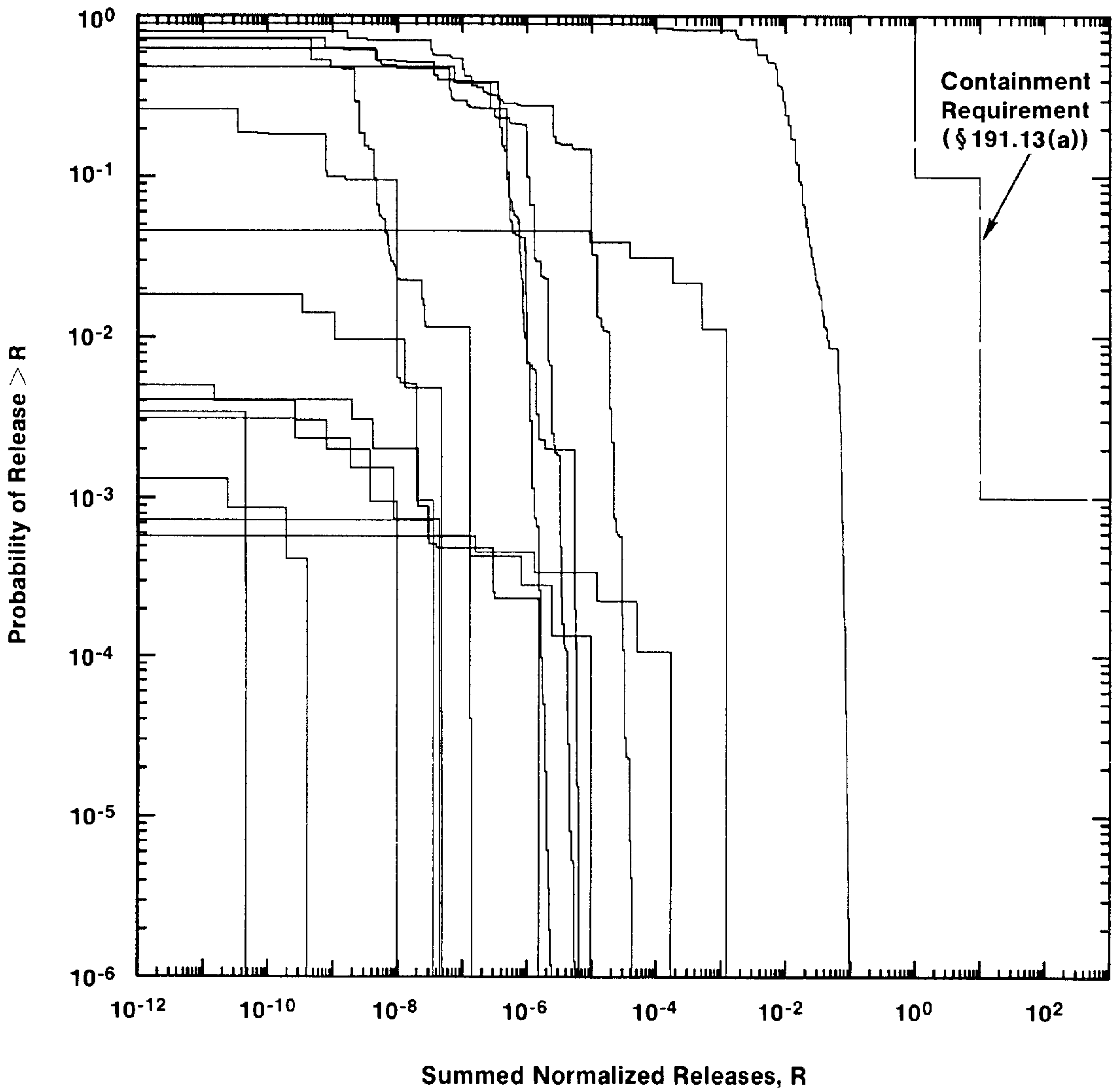
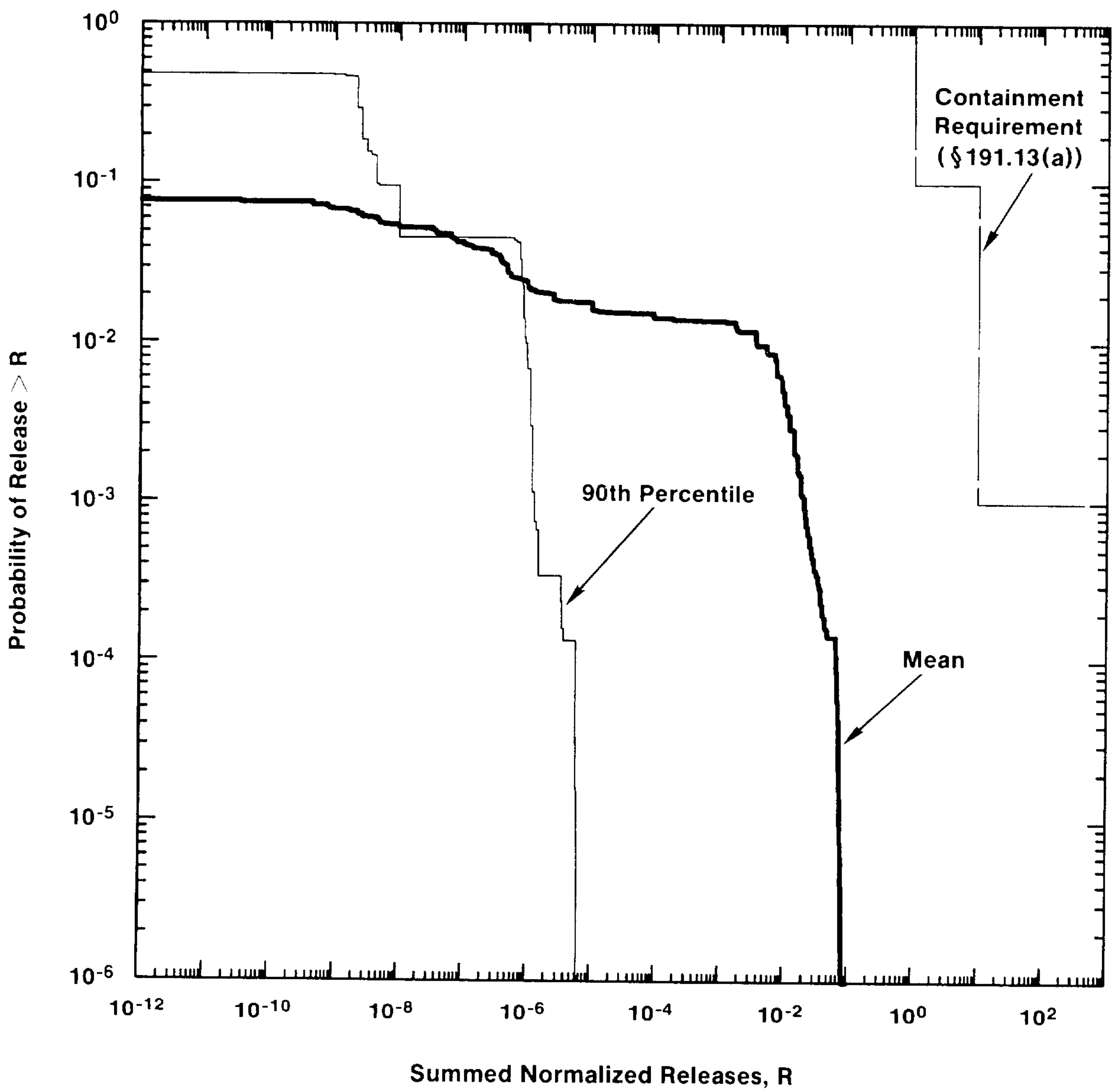


Figure 6-2. Mean, Median, 10th, and 90th Percentile CCDFs Derived from the Family of CCDFs Shown in Figure 6-1. Curves show total cumulative normalized releases to the accessible environment resulting from both groundwater transport in the subsurface and releases at the surface during drilling. CCDFs are conditional on assumed scenarios, models, and distributions for parameter values, as described in the text and in Volumes 2 and 3 of this report.



TRI-6342-1295-0

Figure 6-3. Family of CCDFs Showing Cumulative Normalized Releases to the Accessible Environment Resulting from Groundwater Transport in the Subsurface. CCDFs are conditional on assumed scenarios, models, and distributions for parameter values, as described in the text and in Volumes 2 and 3 of this report.



TRI-6342-1296-0

Figure 6-4. Mean and 90th Percentile CCDFs Derived from the Family of CCDFs Shown in Figure 6-3. The median and 10th percentile CCDFs are off the plot to the left. Curves show cumulative normalized releases to the accessible environment resulting from groundwater transport in the subsurface. CCDFs are conditional on assumed scenarios, models, and distributions for parameter values, as described in the text and in Volumes 2 and 3 of this report.

The main consequence modeling differences between the 1990 and 1991 preliminary comparisons are the inclusion of variable climate, dual-porosity transport, and waste-generated gas effects. The main probability modeling differences are the assumption that drilling intrusions are a Poisson process, the inclusion of uncertainty in the characterization of stochastic variability instead of using fixed probability estimates for summary scenarios, and the refinement of summary scenarios into many computational scenarios. An analysis of the effects of these changes is presented in Volume 4 of this report.

Chapter 6-Synopsis

Conceptual Model for Risk

Construction of CCDFs presented in this chapter is based on the conceptual representation of performance assessment described in Chapter 3 of this volume.

Scenarios Included and Probability Estimates

The base-case summary scenario is not analyzed for comparison with the Containment Requirements (disturbed performance) because no releases are estimated to occur in the 10,000-year regulatory period. However, the base case summary scenario is included in CCDF construction through its estimated probability and zero consequences.

Families of CCDFs are displayed so that stochastic variability and uncertainty due to imprecisely known variables are clearly separated. Portraying the summary scenarios in this manner requires further refining of the summary scenarios into computational scenarios that are separate sets of common occurrences with similar consequences for all elements of each computational scenario. In addition, separation into computational sets allows estimating consequences with reasonable computational cost.

The factors, which all relate to stochastic or Type A uncertainty, that are used to define the sets of computational scenarios are

number and time of intrusions,

flow through a panel due to penetration of a pressurized brine reservoir in the Castile Formation,

activity level of the waste penetrated by a borehole.

For the 1991 performance assessment,

drilling intrusions are assumed to occur randomly in space and time with a fixed rate constant (follow a Poisson process). For this performance assessment, the regulatory time interval of 10,000 years is divided into five time intervals of 2,000 years, with intrusion occurring at the midpoints of these intervals (at 1000, 3000, 5000, 7000, and 9000 years).

the waste panels are assumed to be underlain by one or more pressurized brine reservoirs in the Castile Formation.

four CH activity levels and one RH activity level are defined to represent variability in the activity level of waste penetrated by a drilling intrusion.

Fundamental differences between this year's and previous years' performance assessments are

refinement of summary scenarios into computational scenarios,

the use of the Poisson assumption for calculating scenario probabilities.

The CCDF construction procedure used for this year's performance assessment results in an explicit representation for the effects of stochastic variability.

Imprecisely Known Parameters

Forty-five imprecisely known parameters were sampled for use in consequence modeling for the Monte Carlo simulations of performance. For each, a range and distribution were assigned.

Fundamental differences from last year's performance assessment are the addition of

parameters related to two-phase flow and gas generation,

parameters related to dual porosity (both chemical and physical retardation) in the Culebra,

a set of conditional simulations for transmissivity in the Culebra instead of the 1990 simple zonal approach, a preliminary analysis of potential effects of climatic variability on flow in the Culebra.

Sample Generation

Latin hypercube sampling is used to incorporate uncertainty due to imprecisely known variables, or Type B uncertainty, into the performance assessment.

For the 1991 performance assessment, a Latin hypercube sample of size 60 was generated from the set of 45 variables.

Decomposition into computational scenarios is a form of stratified sampling in which Type A uncertainty is incorporated into the performance assessment and forces the inclusion of low-probability, high-consequence computational scenarios.

Consequence Modeling

After the sample is generated, each element of the sample is propagated through the system of computer codes used for scenario analysis. Only computational scenarios for human intrusion are included.

In the 1991 performance assessment, the major computer modules used to simulate flow and transport are CUTTINGS, BRAGFLO, SECO2D, AND STAFF2D.

Each sample was used in calculating both cuttings/cavings and subsurface groundwater releases for intrusion times of 1000, 3000, 5000, 7000, and 9000 years for E1- and E2-type intrusions. Consequences of E1-type intrusion were found to be similar to and bounded by E1E2-type intrusions, so only the latter required calculations.

The resulting set of consequences (cuttings/cavings plus subsurface groundwater releases) were used by the probability computer model CCDFPERM to calculate a family of CCDFs and its summary curves (median, mean, and various quantiles).

1991 Performance Assessment CCDFs

Based on the performance-assessment data base and present understanding of the WIPP disposal system, the summary curves showing total cumulative normalized releases to the accessible environment resulting from both groundwater transport in the subsurface and releases at the surface during drilling (Figure 6-2) are considered to be the most realistic choices for preliminary comparison with the Containment Requirements.

Except for a few low-probability releases, cuttings/cavings dominates the CCDFs for total releases.

The main differences in modeling consequences between the 1990 and 1991 preliminary comparisons are the inclusion of

variable climate,

dual-porosity transport,

waste-generated effects.

The main differences in modeling probabilities between the 1990 and 1991 preliminary comparisons are

the assumption that drilling intrusions are a Poisson process,

the inclusion of uncertainty in the characterization of stochastic variability instead of using fixed probability estimates for summary scenarios,

the refinement of summary scenarios into many computational scenarios.

7. INDIVIDUAL PROTECTION REQUIREMENTS

[*NOTE: The text of Chapter 7 is followed by a synopsis that summarizes essential information, beginning on page 7-6.*]

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).

The Standard requires that an uncertainty analysis of undisturbed conditions be performed to assess compliance with § 191.15. In the case of the WIPP, the performance measure is dose to humans in the accessible environment. Evaluations thus far 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 time periods. Performance assessments will evaluate compliance with the Individual Protection Requirements of the 1985 Standard until a revised Standard is promulgated.

7.1 Previous Studies

Three previous studies reported doses to humans resulting from hypothetical releases from the WIPP for selected scenarios (U.S. DOE, 1980a; Lappin et al., 1989; Lappin et al., 1990). 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. Undisturbed performance was evaluated probabilistically by Marietta et al. (1989) in a methodology demonstration for WIPP performance assessment. Calculations for undisturbed performance of the repository were not updated in the 1990 preliminary performance assessment (Bertram-Howery et al., 1990). However, information about possible effects of gas generated within the repository was obtained from the assessment of disturbed performance.

7.1.1 EVALUATION PRIOR TO THE 1985 STANDARD (1980 FEIS)

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 consequence 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, to 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* (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 1000 years for individual protection.

7.1.2 DOSE ESTIMATES (LAPPIN ET AL., 1989)

An analysis of undisturbed conditions for the WIPP was performed (Lappin et al., 1989) for two different cases in support of the WIPP supplemental environmental impact statements (SEIS) (U.S. DOE 1989b, 1990c). The exposure pathway considered was radionuclide transport through the sealed shafts and intact Salado to the Culebra Dolomite, downgradient through the Culebra to a hypothesized stockwell at the nearest location where Culebra water might be potable for cattle, and then to humans via beef ingestion. Calculations were deterministic, with one case using expected parameter values and the other case using degraded parameter values. The study indicated that, in the absence of human intrusion, there would be no releases to the Culebra in 1000 years. Therefore, no doses were calculated for undisturbed conditions.

7.1.3 1989 METHODOLOGY DEMONSTRATION

The next evaluation of undisturbed performance of the WIPP was the methodology demonstration of Marietta et al. (1989). Undisturbed performance was simulated using the base-case scenario (Guzowski, 1990). The repository was assumed to be consolidated, and all legs in the flow path were assumed to be saturated from the time of repository decommissioning. Uncertainty analysis was based on probability density functions representing realistic but preliminary estimates of minimum, maximum, and expected or median values and distributions of parameters.

In the simulations for the methodology demonstration, no releases from the repository/shaft system to the Culebra occurred during the 1000 years of regulatory concern. Because of the slow rate of radionuclide movement, simulations were extended to 50,000 years to assess system performance. Even at this longer time interval, no significant releases to the Culebra occurred. Results were therefore presented in terms of radionuclide migration through the MB139 seal below the repository and to the base of the shaft.

The demonstration analysis for undisturbed conditions indicated no releases from the repository in either the 1000-year period for the Individual Protection Requirements (§ 191.15) or the 10,000-year period for the Containment Requirements (§ 191.13). The fact that no releases occurred indicated that no dose calculations were needed for demonstrating compliance with the Individual Protection Requirements of the 1985 Standard.

7.1.4 SENSITIVITY ANALYSES (RECHARD ET AL., 1990)

Rechard et al. (1990a) examined the relative importance of various phenomena and system components through sensitivity analyses of four different repository shaft models for undisturbed conditions. Although these simulations did not calculate EPA sums or doses to humans for either the Containment or Individual Protection Requirements, they did calculate brine flow in the lower shaft seals, which bears directly upon estimating releases to the Culebra.

The first two models considered only one-phase (brine) flow: a two-dimensional model of brine flow into MB139, and a cylindrical model of brine flow through a waste panel into a shaft. The second two models considered effects of gas flow: a two-dimensional model simulating gas flow through drifts, and a one-dimensional model of two-phase (brine and gas) flow through MB139.

The following conclusions were drawn: for brine-saturated conditions, flow from the repository occurs in all directions when expected parameter values are used, but for degraded parameter values, a primary path along MB139 exists. The two-phase calculations that assessed gas migration to the shaft indicated that brine would retard such flow unless well-fractured, high-permeability paths exist as in MB139 and anhydrite layers A and B. This work indicated that two-phase models including local stratigraphy (MB139, anhydrite layers A and B) were required for simulating undisturbed conditions.

7.1.5 DOSE ESTIMATES (LAPPIN ET AL., 1990)

The two cases reported by Lappin et al. (1989) were repeated by Lappin et al. (1990) with revised assumptions. Changes were the following: a shorter pathway from the northern equivalent panel instead of the northeast panel was used; both hydrostatic and lithostatic driving pressures were used to bound the problem; and MB139 properties were revised to include improved understanding of the DRZ and to update seal design. Again, there were no radionuclide releases to the Culebra Dolomite in 10,000 years, and therefore, no dose calculations were performed for undisturbed conditions.

7.1.6 1990 PRELIMINARY COMPARISON

Calculations for undisturbed performance of the WIPP repository were not updated in the 1990 preliminary performance assessment (Bertram-Howery et al., 1990). However, results from preliminary simulations of two-phase (gas and brine) flow provided some data on the possible effects of gas generation within the repository during the first 1000 years after decommissioning. The analysis used two-dimensional, two-phase flow simulations with idealized room geometry and local stratigraphy to evaluate the effect of gas on repository performance. Simulations assumed panel seals that would consolidate to intact halite properties in the drift but no seal in either MB139 or the anhydrite layers A and B. The gas-generation rate was fixed at 2 moles/drum/year, the maximum rate for hydrogen generation postulated by Lappin et al. (1989). (As discussed in Volume 3 of this report, the gas-generation rate has since been revised.)

Preliminary results from the simulations suggested that in the undisturbed state, gas saturation would be high in the upper portion of the waste, MB139, and the overlying anhydrite layers. As calculated, gas migration away from a room within the excavated volume and the DRZ would occur over a length scale longer than the drift length from the northernmost panel seal to the closest shaft. In the simulations, gas saturation is near maximum at the shaft/drift interfaces, meaning that transport of dissolved radionuclides, which requires a liquid medium, would be diminished. In addition, brine content in the waste would be diminished due to the presence of gas, so less brine would be available to transport radionuclides, and very little gas or brine would move into the lower permeability, intact halite surrounding the fractured anhydrite and the DRZ.

7.2 Results of the 1991 Preliminary Comparison

All previous assessments of repository performance for undisturbed conditions have not fully addressed potential effects of waste-generated gas. Therefore, updated analyses of undisturbed conditions for Individual Protection (191.15) and Containment (191.13) Requirements were performed. As described, earlier analyses have estimated that there would be no releases to the Culebra Dolomite and, therefore, to the accessible environment 5 km downgradient (Figure 1-3) in 10,000 years. Based on these earlier analyses, the approach adopted for the 1991 performance assessment is to perform deterministic calculations to verify that previous conclusions of no releases in 10,000 years are still valid with the 1991 modeling system including gas effects, current data, and current conceptual models. Two sets of calculations were performed and are fully described in Volume 2 of this report. These calculations have been designed to provide a conservatively large estimate of potential releases to the accessible environment. Because of the complexity of the interdependent processes being modeled, it is not possible to assert that results of these calculations bound potential releases.

First, a two-dimensional simulation to assess the migration of brine from the repository into the intact portion of MB139 was done. This calculation estimates the spatial scale that passive, neutrally bouyant particles would be transported in advecting brine as a result of maximum gas-generation rates in a waste panel. A pressure-time history was calculated for maximum corrosion and biodegradation rates with a two-phase, two-dimensional simulation using BOAST II. Brine flow, pollutant concentration, and particle transport were calculated with a one-phase, two-dimensional simulation using SUTRA with the pressure-time history from BOAST II. Assuming least-favorable bounds for important parameter values results in the 1% (of initial source) contour occurring at less than 120 m from the waste panel at 10,000 years. The accessible-environment boundary is located 5 km from the waste panels, so this pathway is not considered further.

Second, a two-dimensional vertical section simulation of the repository from waste panels to the closest shaft to assess migration of radionuclides through the DRZ, panel seals, and backfilled excavations was done. The calculation estimates the extent that radionuclides would be transported in brine flowing towards and upwards through sealed shafts as a result of the pressure gradient between the Culebra Dolomite and a waste panel that is pressurized with waste-generated gas. Again, a pressure-time history (BOAST II) resulting from maximum gas-generation rates of corrosion and biodegradation was used to calculate (STAFF2D and SUTRA) brine advection, pollutant concentration, and particle tracking (pathways and travel times). In this case, a measure of radionuclude migration at different locations should be reported. The appropriate measure for comparison to the Containment Requirements is the normalized EPA sum (EPA Sum); for the Individual Protection Requirements the measure should be peak concentration, but if there are zero releases, both measures are zero. Therefore, EPA Sums are reported 20 and 50 m up the shaft above the intersection with the repository horizon and 100 and 200 m into the intact MB139 (away from the shaft) (see Volume 2, Chapter 4 of this report). Assuming least favorable bounds for important parameter values (e.g., an inexhaustible source, no decay, no retardation, the same solubility limit for all radionuclides, etc.) results in EPA Sums less than 10^{-2} at 20 m and less than 10^{-3} at 50 m up the shaft from the repository horizon. Therefore, there are no significant releases at the shaft/Culebra intersection at 10,000 years. The accessible-environment boundary is 5000 m downgradient in the Culebra, so this pathway results in zero releases to the accessible environment in 10,000 years. EPA Sums at 100 and 200 m into MB139 away from the shaft are less than 10^{-2} and 10^{-5}, respectively. For the Containment Requirements the undisturbed scenario is not analyzed further, and consequences (EPA Sums) of this scenario are all zero in the CCDF construction of Chapter 6 of this volume. Probability of the undisturbed scenario must still be included (Figure 3-13). For the Individual Protection Requirements, there are no releases to the accessible environment in 1000 years, so dose calculations are not required.

After performing these calculations, which are somewhat stylized, it was believed to be prudent to check diagnostic information from the Monte Carlo simulations for the Containment Requirements reported in Chapter 6 of this volume. In that set of analyses, 120 simulations of computational scenarios were run for human intrusion occurring at 1000, 3000, 5000, 7000, and 9000 years, for a total of 600 simulations. Before intrusion occurs, these calculations simulate undisturbed conditions. Simulations of the 1000-year intrusion time apply directly to the Individual Protection Requirements. The two-phase BRAGFLO calculations should be compared to the first description of calculations in the above discussion because only a waste panel and surrounding stratigraphy are modeled.

Chapter 7-Synopsis

The Standard requires that an uncertainty analysis of undisturbed conditions be performed to assess compliance with the Individual Protection Requirements. For the WIPP, the performance measure is dose to humans in the accessible environment.

Evaluations thus far 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 the Standard.

Previous Studies

Evaluation Prior to the 1985 Standard (1980 FEIS)

The Final Environmental Impact Statement (FEIS) estimated the consequence of five different hypothetical scenarios that might move radionuclides to the biosphere.

The pathway included radionuclide movement through the geosphere, transport through the biosphere after discharge into the Pecos River at Malaga Bend, and receipt of radiation doses by humans.

The travel times for radionuclides arriving at Malaga Bend were on the order of a million years.

Dose Estimates (Lappin et al., 1989)

This analysis of undisturbed conditions for the WIPP was performed in support of the supplemental environmental impact statements (SEIS).

The exposure pathway was radionuclide transport through the sealed shafts and intact Salado to the Culebra Dolomite, downgradient through the Culebra to a hypothesized stock well at the nearest location where Culebra water might be potable for cattle, and then to humans via beef ingestion.

The study indicated that, in the absence of human intrusion, no releases would occur in 1000 years.

1989 Methodology Demonstration

For this evaluation, undisturbed performance was simulated through a base-case scenario. The repository was assumed to be consolidated, and all legs in the flow path were assumed to be saturated from the time of repository decommissioning.

The simulations indicated that no releases from the repository/shaft system to the Culebra occurred during the 1000 years of regulatory concern for undisturbed performance. Even for a simulation with a longer time interval of 50,000 years, no significant releases to the Culebra occurred.

The fact that no releases occurred indicated that no dose calculations were needed for demonstrating compliance with the Individual Protection Requirements of the 1985 Standard.

Sensitivity Analysis (Rechard et al., 1990)

The relative importance of various phenomena and system components through sensitivity analyses of four different repository/shaft models for undisturbed conditions was analyzed.

Conclusions of the study were the following:

For brine-saturated conditions, flow from the repository occurs in all directions when expected parameter values are used, but for degraded parameter values, a primary path along MB139 exists.

Two-phase calculations that assessed gas migration to the shaft indicated that brine would retard such flow unless well-fractured, high-permeability paths exist as in MB139 and anhydrite layers A and B.

Two-phase models including local stratigraphy (MB139, anhydrite layers A and B) were required for simulating undisturbed conditions.

Dose Estimates (Lappin et al., 1990)

This evaluation revised the cases of Lappin et al. (1989) by using a shorter pathway within the repository, both hydrostatic and lithostatic driving pressures to bound the problem, and MB139 properties that included improved understanding of the DRZ and updated seal design.

No radionuclide releases to the Culebra Dolomite occurred in 10,000 years, and therefore, no dose calculations were performed for undisturbed conditions.

1990 Preliminary Comparison

In lieu of calculations for undisturbed performance, results from preliminary simulations of two-phase (gas and brine) flow provided some data on possible effects of gas generation within the repository during the first 1000 years after decommissioning.

Preliminary results from the simulations suggested that, in the undisturbed state,

gas saturation is near maximum at the shaft/drift interfaces, meaning that transport of dissolved radionuclides, which requires a liquid medium, would be diminished,

brine content in the waste would be diminished due to the presence of gas, so less brine would be available to transport radionuclides,

very little gas or brine would move into the lower permeability, intact halite surrounding the fractured anhydrite and the DRZ.

Results of the 1991 Preliminary Comparison

The approach adopted for the 1991 performance assessment is to perform deterministic calculations to verify that, using the 1991 modeling system, previous conclusions of no releases in 10,000 years are still valid.

First, a two-dimensional horizontal simulation to assess the migration of brine from the repository into the intact portion of MB139 was performed. The calculation estimates the spatial scale that passive, neutrally buoyant particles would be transported in advecting brine as a result of maximum gas-generation rates in a waste panel.

Second, a two-dimensional simulation of a vertical section of the repository from waste panels to the closest shaft was performed to assess migration of radionuclides through the DRZ, panel seals, and backfilled excavations. The calculation estimates the extent that radionuclides would be transported in brine flowing towards and upwards through sealed shafts as a result of the pressure gradient between the Culebra Dolomite and a waste panel that is pressurized with waste-generated gas.

Least favorable bounds for important parameter values (e.g., an inexhaustible source, no decay, no retardation, the same solubility limit for all radionuclides, etc.) are assumed.

Results of the horizontal simulation show concentrations in the intact MB139 after 10,000 years at 1% of the source 120 m from the panels. Results of the vertical simulation including the shaft show EPA normalized sums at 10,000 years of less than 10^{-2} at 20 m up the shaft and less than 10^{-3} at 50 m up the shaft. Therefore, no significant releases occur at the shaft/Culebra intersection at 10,000 years.

For the Individual Protection Requirements, no releases to the accessible environment occur in 1000 years, so dose calculations are not required.

8. ASSURANCE REQUIREMENTS PLAN

[*NOTE: The text of Chapter 8 is followed by a synopsis that summarizes essential information, beginning on page 8-10.*]

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, 1987). 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, Westinghouse Electric Corporation (see Chapter 1 of this volume), updates the implementation plans. A draft of the revised *Assurance Requirements Plan* (U.S. DOE, 1987) is in review, with publication expected before year-end 1991. 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. Additional information on markers as passive institutional controls comes from performance-assessment activities using expert panels. This chapter summarizes plans for implementing the Assurance Requirements.

8.1 Active Institutional Controls

Active institutional controls are expected to include evaluation of land use in the WIPP area; maintaining fences and buildings and guarding the facility during active cleanup; decontamination and decommissioning; land reclamation; and post-operational monitoring. The objectives of these activities are to provide a facility and presence at the site during active cleanup, to restore the land surface as closely to its original condition as possible to avoid future preferential selection of the area for incompatible uses, 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.

8.2 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 but are likely to include monitoring of hydrological, geological, geochemical, and structural performance. Numerous subsidence monuments have been installed to monitor subsidence as an indicator of unexpected changes in the disposal system.

8.3 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.

8.3.1 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 or elements to physically deter human intrusion (and warn potential intruders that drilling, excavation, etc., should cease for safety reasons). The guidance also suggests that the effectiveness of passive institutional controls such as markers should be estimated.

In an effort to address the issue of markers for the WIPP, two expert panels have been established. Members of the first panel, whose work has already been completed, were asked to (1) identify possible future societies and how they may intrude the repository, and (2) develop probabilities of future societies and probabilities of various intrusions. The possible modes of intrusion identified by the future-intrusion experts were provided to the marker-development experts as the starting point as they (1) develop design characteristics for "permanent" markers, and (2) judge the efficacy of the markers in deterring human intrusion.

The work of the future-intrusion panel is described in Chapter 4 of this volume, along with a discussion of the expert-judgment process. The procedure used for selection of the marker-development experts was the same as that described earlier for the future-intrusion experts. Nominations were solicited from 75 nominators, resulting in a total of 92 nominations. Letters of interest were received from 57 nominees. 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 marker-development panel met in November 1991 and will meet again in January 1992. Background information (introduction to the WIPP; performance assessment and the Standard; scenario development and modeling; the geology, hydrology, and climate of the WIPP; and a review of previous marker work) were provided to the panelists at the first meeting, and several future-intrusion experts returned to describe their efforts. These initial presentations led into a discussion of the issue statement, which delineated the specific points regarding marker development that must be addressed by the panel. Training was provided to assist the experts in the development of probability distributions describing the efficacy of markers in deterring human intrusion. In addition, the marker-development experts toured the WIPP to better understand the physical setting. The period between the two meetings will be used by the panelists to review the materials provided to them, to develop a response to the issue statement, and to prepare draft documentation describing the approach used to respond. The second meeting will involve discussion between the two teams on their respective approaches and elicitation of probability distributions. After the second meeting, the documentation will be revised based on the results of the discussions and the elicitation sessions. The probability estimates of the marker-development experts will be documented, organized, and returned to the experts for comment and review. Following concurrence by the experts, the results will be documented for performance assessment and published as a Sandia National Laboratories report (SAND report).

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 (incorporating judgment from 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 estimate the probabilistic performance of various types of markers. These estimates will be formally elicited.

A consultant is preparing material that describes past efforts at developing barriers to human intrusion and some considerations pertaining to such development, as a complement to the markers. An expert panel may be convened in the future to further investigate this strategy.

8.3.2 FEDERAL OWNERSHIP

In accordance with Appendix B of the Standard, the DOE or some successor agency is assumed to retain ownership and administrative control over the land. 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.

8.3.3 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 provided estimates on how effective records will 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.

8.4 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 the favorable characteristics of the salt formation 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 Alternatives Task Force to evaluate additional engineering measures for the WIPP should such measures be necessary.

8.5 Natural Resources

The Standard requires that locations containing recoverable resources not be used for repositories unless the favorable characteristics of a proposed 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 recently published *Implementation of the Resource Disincentive in 40 CFR Part 191.14(e) at the Waste Isolation Pilot Plant* provides the supporting documentation (U.S. DOE, 1991d).

In the report, evaluation of the natural resources in the WIPP area centered on two issues. First, the denial of resources that could not be developed because such development might conflict with the long-term goal of waste isolation was considered. Second, the attractiveness to future generations of resources associated with the location was studied. Future societies might attempt to exploit natural resources near the WIPP and thereby create the potential for a release of radionuclides into the accessible environment.

These issues were evaluated in the *FEIS* (U.S. DOE, 1980a) and other reports (U.S. DOE, 1981; U.S. DOE and State of New Mexico, 1981, as modified; Brausch et al., 1982; Weart, 1983; U.S. DOE, 1990c). The *Resource Disincentive* report (U.S. DOE, 1991d) summarizes from these reports and documents the information about natural resources that the DOE used in making the decision to proceed with the WIPP Project.

In order to conduct resource analyses, the area was originally organized into four control zones (U.S. DOE, 1980a) (Figure 8-1). In 1982, the DOE released control of the outermost control zone (Vaughn, 1982). Comprehensive site characterization activities showed that the WIPP area contains potential economic quantities of both hydrocarbons and potash.

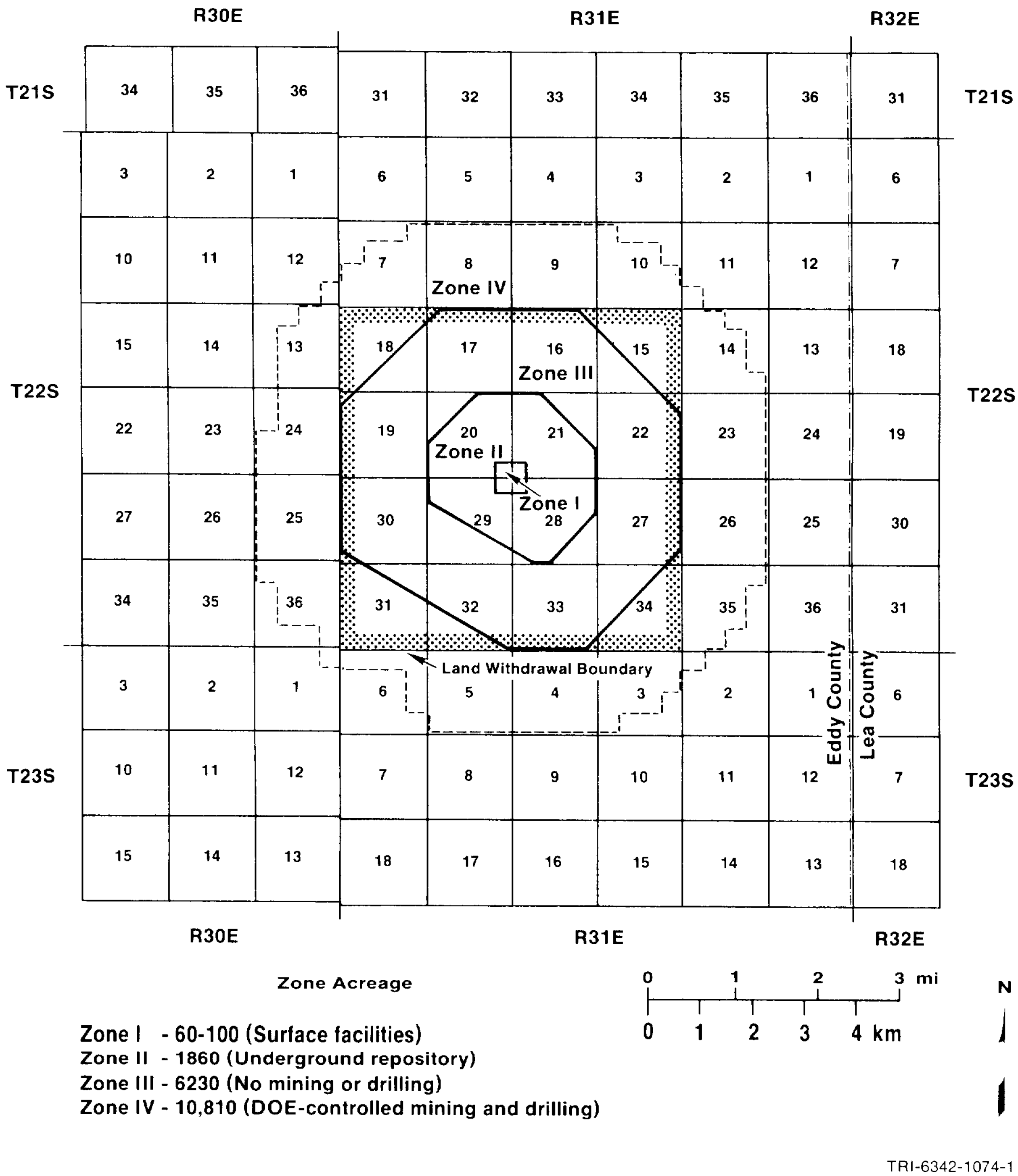


Figure 8-1. Control Zones at the WIPP (Powers et al., 1978a,b).

In order to gain control over the development of hydrocarbons at the WIPP, the DOE acquired the oil and gas leases within all the WIPP control zones. The only leases that are still intact are in Section 31 (Figure 8-1). These leases only allow resource production by entry of the proposed land withdrawal area below 6000 feet. One of these leases is currently in production. The upper 6000 feet of the leases was taken by the DOE in 1979. Current policy does not allow any further resource development inside the proposed land withdrawal boundary (U.S. DOE, 1991d). Estimates were prepared of the hydrocarbon reserves (economically producible resources) within the area (Keesey, 1976). The study was updated immediately prior to publication of the *Draft Environmental Impact Statement* (U.S. DOE, 1979), and reserve estimates were subsequently prepared (Keesey, 1979). The report on the implementation of the resource disincentive at the WIPP (U.S. DOE, 1991d) summarizes the impacts of hydrocarbon resource denial, based on information in the *FEIS* (U.S. DOE, 1980a). The projected impacts of hydrocarbon resource denial at the WIPP are shown in Table 8-1.

The principal nonhydrocarbon mineral resources that underlie the WIPP facility are caliche, gypsum, salt, lithium from brines, sylvite, and langbeinite. With the exceptions of sylvite and langbeinite (Table 8-2), however, the impact of mineral resource denial is relatively insignificant. Langbeinite, a somewhat rare mineral that contains soluble potassium used in making some fertilizers, is present in the WIPP area in limited commercial deposits. Sylvite, an additional evaporite mineral, is sometimes mixed with langbeinite to create the principal beneficial ingredient (potassium sulfate) produced from langbeinite for fertilizers. Denying langbeinite production within the WIPP boundaries would decrease the estimated 28 to 46 years of remaining mining operations in the area by only 4 years. In addition, substitutes for the potassium sulfate in langbeinite are available.

Groundwater in the WIPP area has been studied extensively, and the results have been summarized in the *FEIS* (U.S. DOE, 1980a), the *Final Safety Analysis Report* (U.S. DOE, 1990a), and in Chapters 5 and 9 of this volume. Groundwater exists both above and below the WIPP repository horizon. Below the WIPP, the groundwater in the Bell Canyon Formation is of very poor quality and is usually considered a brine. Units above the repository horizon have low groundwater yields with high concentrations of total dissolved solids (Lappin et al., 1989). Sources of drinking water for substantial populations are not impacted by the WIPP. Alternative supplies of drinking water are available from wells 30 miles north of the WIPP that are completed in the Ogallala Formation (U.S. DOE, 1990a). Groundwater near the WIPP is not vital to the preservation of unique and sensitive ecosystems. Endangered species of plants or animals are not known to inhabit the WIPP area (U.S. DOE, 1980a).

TABLE 8-1. SUMMARY OF HYDROCARBON RESOURCES AT THE WIPP

Deposit	WIPP Total*	Region	United States	World
RESOURCES				
Natural Gas (bill. ft^3)	490	25,013	855,000	N/A
Control Zones I-III	211	0.8%	0.025%	
Control Zone IV	279	1.1%	0.033%	
Distillate (mill. barrels)	5.72	293	N/A	N/A
Control Zones I-III	2.46	0.84%		
Control Zone IV	3.26	1.11%		
Crude Oil (mill. barrels)	37.5	1915	200,000	N/A
Control Zones I-III	16.12	0.84%	0.008%	
Control Zone IV	21.38	1.12%	0.0006%	
RESERVES				
Natural Gas (bill. ft^3)	44.62	3865	208,800	2,520,000
Control Zones I-III	21.05	0.54%	0.01%	0.0008%
Control Zone IV	23.57	0.61%	0.011%	0.0009%
Distillate (mill. barrels)	0.12	169.1	35,500	N/A
Control Zones I-III	0.03	0.02%	0.00008%	
Control Zone IV	0.09	0.06%	0.00024%	
Crude Oil		471.7	29,486	646,000

* Control Zones I-IV (see Figure 8-1)
Source: U.S. DOE, 1991d, based on U.S. DOE, 1980a, p. 9-19 and 9-28.

The presence of hydrocarbons, langbeinite, and other resources has been evaluated from the standpoint of resource attractiveness (U.S. DOE, 1980a; Brausch et al., 1982; U.S. DOE, 1990c). These analyses indicate that the consequence of an inadvertent intrusion into the repository in search of resources is small. The *Resource Disincentive* report (U.S. DOE, 1991d) states that the DOE believes that resource attractiveness does not appear to compromise the adequacy, safety, or reliability of the WIPP. Future studies will continue to evaluate the validity of this assumption.

TABLE 8-2. SUMMARY OF POTASH RESOURCES AT THE WIPP

Deposit	WIPP Total*	Region	United States	World
RESOURCES				
Sylvite (mill. tons ore)	133.2	4260	8550	850,000
Control Zones I-III	39.1	0.92%	0.46%	0.0046%
Control Zone IV	94.1	2.21%	1.10%	0.01%
Langbeinite (mill. tons ore)	351.0	1140	N/A	N/A
Control Zones I-III	121.9	10.7%		
Control Zone IV	229.1	20.1%		
RESERVES				
Sylvite (mill. tons K_2O)	3.66	106	206	11,206
Control Zones I-III	NIL			
Control Zone IV	3.66	3.45%	1.78%	0.33%
Langbeinite (mill. tons K_2O)	4.41	9.3	9.3	N/A
Control Zones I-III	1.21	13.0%	13.0%	
Control Zone IV	3.20	34.4%	34.4%	

* Control Zones I-IV (see Figure 8-1)
Source: U.S. DOE, 1991d, based on U.S. DOE, 1980a, p. 9-19 and 9-28.

The favorable characteristics of the WIPP location formed the basis for the DOE's decision to proceed with full construction and plans for the Test Phase. The DOE concluded that these favorable characteristics are not available at another site and that they more than compensate for the possibility that the site might be disturbed in the future (U.S. DOE, 1991d).

8.6 Waste Removal

The Standard requires that disposal systems be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal (§ 191.14(f)). According to the preamble, "[t]he intent of this provision was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated" (U.S. EPA, 1985, p. 38082).

A primary plan for waste removal during the operational phase of the WIPP (Subpart A of the Standard) has been prepared (U.S. DOE, 1980a). In promulgating the Standard, the EPA stated that to meet § 191.14(f) for the disposal phase (Subpart B of the Standard), it only need be technologically feasible to be able to mine the sealed repository and recover the waste, even at substantial cost and occupational risk (U.S. EPA, 1985, p. 38082). The EPA also stated that "<u>any</u> current concept for a mined geologic repository meets this requirement <u>without</u> any additional procedures or design features" (ibid.). Thus, the WIPP satisfies this requirement.

Chapter 8—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

- provide a facility and presence at the site during active cleanup,
- restore the land surface as closely to its original condition as possible to avoid future preferential selection of the area for incompatible uses,
- 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.

Monitoring activities are likely to include monitoring of hydrological, geological, geochemical, and structural performance.

Passive Institutional Controls

The objectives of passive institutional controls at the WIPP are to deter or minimize inadvertent human intrusion into the repository, as outlined in Appendix B to the Standard.

Current plans for passive institutional controls include

markers warning of the presence of buried nuclear waste and identifying the boundary of the controlled area,

federal ownership,

external records about the WIPP repository.

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, physical deterrents, and warnings,

the effectiveness of passive institutional controls such as markers should be estimated.

A two-step process using expert panels addresses the issue of markers for the WIPP:

The future-intrusion experts identified possible future societies and possible types of intrusions of the repository by those societies. The experts also developed probabilities of various intrusions based on the probability of existence of the identified societies.

The determinations of the future-intrusion experts will be used by the marker-development experts in developing design characteristics for "permanent" markers and judging the efficacy of the markers in deterring human intrusion.

Research describing past efforts in developing barriers to human intrusion has also begun. An expert panel may be convened if this approach is deemed a necessary complement to placing markers at the WIPP.

Federal Ownership of the WIPP

In accordance with the Standard, the DOE or a successor government agency is assumed to own and control the land and institute regulations that restrict land use and development.

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 manmade barriers be used as part of the isolation system.

At the WIPP, natural barriers include

- the favorable characteristics of the salt formation,
- the features of the geohydrologic setting.

Manmade barriers include

- backfills,
- seals that isolate volumes of wastes.

The effectiveness of these barriers is being modeled for the performance assessment.

Natural Resources

The issues of denial and attractiveness of hydrocarbon and potash resources, the most significant resources in the WIPP area, have been evaluated.

Studies indicate that hydrocarbon resources represent only a small percentage of U.S. and world supplies.

Although langbeinite, a potash mineral, is relatively rare, substitutes for the soluble potassium used to make potassium sulfate for the chemical and fertilizer industries are available.

Previous analyses have indicated that the consequence of inadvertent intrusion into the repository in search of resources is small. Ongoing studies will continue to evaluate this assumption.

The DOE has determined that the WIPP Project 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 remove 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.

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9. GROUNDWATER PROTECTION REQUIREMENTS

[NOTE: The text of Chapter 9 is followed by a synopsis that summarizes essential information, beginning on page 9-5.]

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 within the maximum extent allowed by the Standard (Figure 9-1) 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.

The following sections address these criteria.

9.1 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 vulnerability to contamination. The classes apply to groundwater having

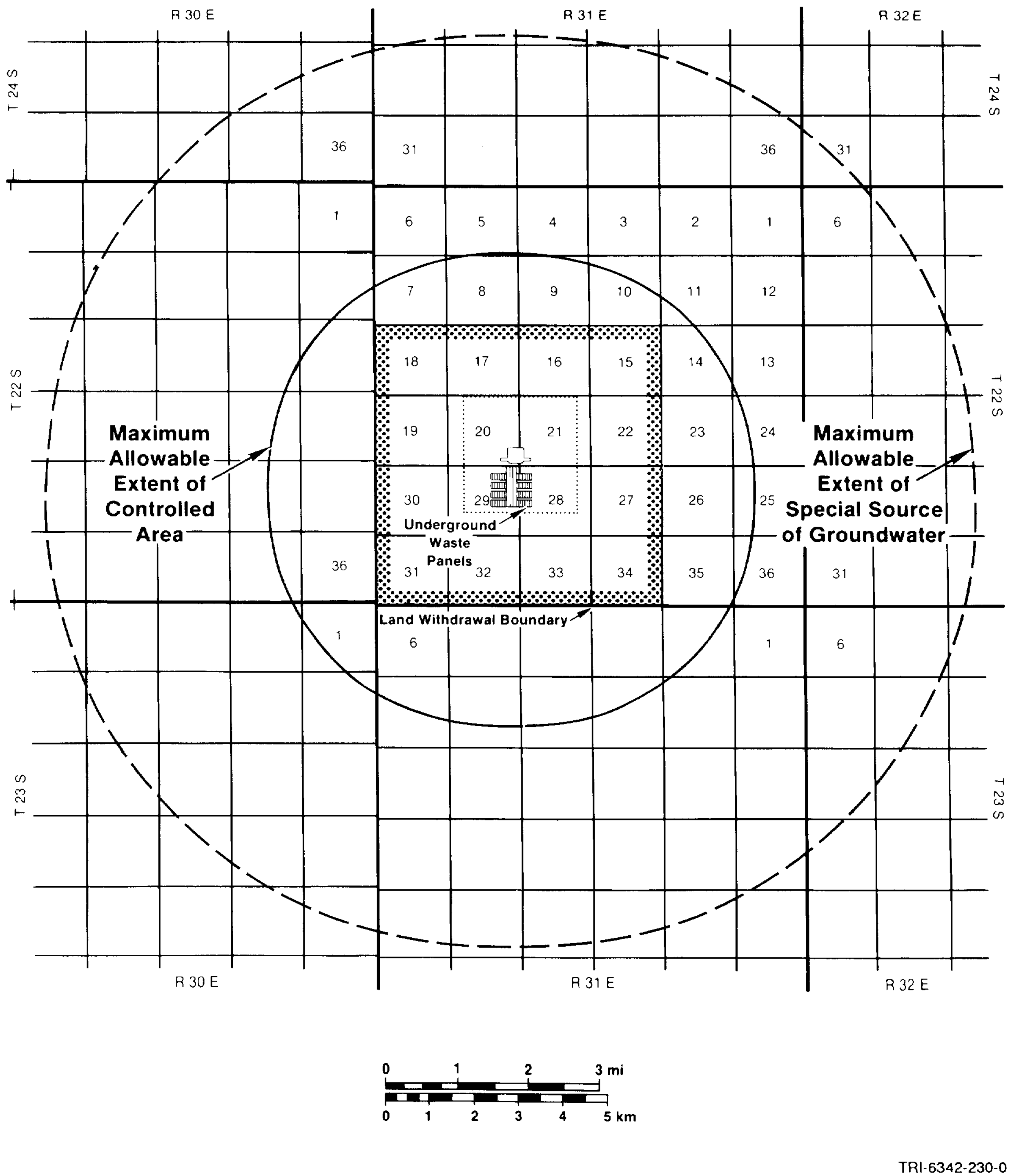

Figure 9-1. Illustration of Certain Definitions (from U.S. DOE, 1989a). The dashed line, drawn 5 km (3 mi) from the maximum allowable extent of the controlled area (§ 191.12(g)), shows the maximum area in which the occurrence of a special source of groundwater (§ 191.12(o)) is of regulatory interest.

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, 1990f). Groundwater quality and the hydrologic conductivity of water-bearing units at the WIPP are monitored and reported annually (U.S. DOE, 1989c).

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. Within the approximately 10.5-km radius dictated by § 191.12(o), the Culebra has hydraulic conductivities ranging from 2×10^{-4} m/s (60 ft/d) to 2×10^{-10} m/s (6×10^{-5} ft/d) (Brinster, 1991). Horizontal groundwater flow in the Culebra is generally to the south along a decreasing gradient at a very slow rate.

Based on hydrogeological studies in the WIPP area, no geological units with high hydraulic conductivities that would require special protective measures appear to be present:

> The hydrologic system near the WIPP does not appear to be a significant groundwater recharge zone. The Culebra Dolomite is separated from overlying rocks by an anhydrite with a lower hydraulic conductivity than that of the Culebra. In wells located to the east of Livingston Ridge, the depth from the surface to the middle of the Culebra Dolomite is consistently greater than 125 m (410 ft) (Marietta et al., 1989). 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..." (Lappin et al., 1989).
>
> The WIPP area is not characterized by a high water table overlain by thin and highly permeable soils. Much of the area includes underlying beds of caliche and siltstone 10 feet or less below the ground surface that apparently prevent large volumes of water from moving downward (U.S. DOE, 1990f).

Even if groundwater that is highly vulnerable to contamination was present near the WIPP, it would not be classified as Class I because it does not meet either the second or third criterion:

> Groundwater near the WIPP is not an irreplaceable source of drinking water for a substantial population because low yields of water-bearing units and high concentrations of total dissolved solids in the groundwater severely limit its use. Uses of water from the Culebra Dolomite are restricted mostly to stock watering; none is used for domestic purposes. Total dissolved solids concentrations in Culebra groundwater in the vicinity range from 2,500 to 240,000 mg/ℓ (Lappin et al., 1989).
>
> Groundwater at the WIPP is not "ecologically vital" because it does not contribute "to maintaining base flow or water level for a particularly sensitive ecological system that, if polluted, would destroy a unique habitat..." (U.S. EPA, 1984). Endangered species of plants or animals are not known to inhabit the WIPP area (U.S. DOE, 1980a).

9.1.1 DRINKING WATER SUPPLY

Class I groundwater is not present in the vicinity of the WIPP; therefore, 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) beyond 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.

9.1.2 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.

Chapter 9–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) beyond 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.

10. COMPARISON TO THE STANDARD

The preliminary performance assessment reported in this document should not be formally compared to the requirements of the Standard to determine whether the WIPP disposal system complies with Subpart B. The disposal system is not adequately characterized, and necessary models, computer programs, and data bases are incomplete. In addition, the final version of the EPA Standard has not been promulgated.

Instead, the discussion in this chapter examines the adequacy of the available information for producing a comprehensive comparison to the Containment Requirements (§ 191.13) and the Individual Protection Requirements (§ 191.15). Adequacy of repository performance will be determined primarily by qualitative judgment regarding "reasonable expectation" of meeting the requirements in § 191.13 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.

10.1 Containment Requirements (§ 191.13)

The Containment Requirements specify probabilistically predicting cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal, taking into account all significant processes and events that may affect the disposal system. Based on these and additional guidelines in the Containment Requirements, significant processes and events have been screened and combined to form the scenarios for which releases will be estimated. Judgment from an expert panel will contribute to the process of determining scenario probabilities.

Because the calculations to quantitatively assess compliance are complex, the executive computer program CAMCON is being developed to link specific numerical models into a single computational system capable of generating the Monte Carlo simulations required for probabilistic performance assessments. As Table 5-1 in Chapter 5 of this volume indicates, several of the individual computer programs required to complete CAMCON are currently under development or are incomplete.

Information continues to be added to the compliance-assessment data bases. In the absence of experimental data that might better define certain parameters, panels are being convened to provide the performance-assessment team with judgment based on the expertise of the panel members. Thus far, expert panels have provided a range of values for radionuclide solubility and the source term for transport calculations and for distribution coefficients (K_ds) used in determining radionuclide retardation in the Culebra Dolomite Member of the Rustler Formation. Additional expert panels are planned to quantify other parameters and thus address the uncertainty in using those data sets.

The Containment Requirements state that compliance will be judged on the basis of a "reasonable expectation" of acceptable performance. Although the Standard does not define "reasonable expectation," it does indicate that compliance assessments should include both quantitative numerical simulations of disposal-system performance and qualitative expert judgment. In addition to expert evaluation of future human actions and parameter values unattainable from experimental data, expert judgment will also define the term "reasonable expectation" to guide probabilistic predictions of the WIPP's performance (Bertram-Howery and Swift, 1990).

The compliance-assessment system can be used for sensitivity and uncertainty analyses and is adequate for preliminary performance studies of the WIPP. Results of the 1991 performance-assessment calculations are in Chapter 6 of this volume.

10.2 Assurance Requirements (§ 191.14)

The Assurance Requirements were included in the Standard to provide the confidence needed for long-term compliance with the Containment Requirements. To address the provisions of the Assurance Requirements, the WIPP Project has prepared *A Plan for the Implementation of Assurance Requirements in Compliance with 40 CFR Part 191.14 at the Waste Isolation Pilot Plant*, DOE/WIPP 87-016. This plan, which was published in 1987, is currently being revised. The revised plan should be available by year-end 1991.

10.2.1 ACTIVE INSTITUTIONAL CONTROLS (§ 191.14(a))

This subsection of the Assurance Requirements specifies that active institutional controls should be maintained over disposal sites for as long as is practicable after disposal. Active institutional controls are expected to include

evaluation of land use in the WIPP area,

maintaining fences and buildings and guarding the facility during the operational phase, decontamination and decommissioning,

land reclamation,

post-operational monitoring.

Many of these activities will not commence until waste disposal has been completed. All performance-assessment calculations begin 100 years after the WIPP is decommissioned. Active institutional controls are thus assumed to be maintained for 100 years, the maximum time allowed by the Standard.

10.2.2 DISPOSAL SYSTEM MONITORING (§ 191.14(b))

Monitoring the disposal system after waste disposal is expected to detect any "substantial and detrimental deviations" from expected performance if they occur. Specific monitoring activities will be identified during evaluation of the WIPP and are likely to include monitoring of hydrological, geological, geochemical, and structural performance.

Monuments have been installed to monitor subsidence as an indicator of unexpected changes in the disposal system. Additional monitoring activities will commence as the necessary types and methods of monitoring are identified.

10.2.3 PASSIVE INSTITUTIONAL CONTROLS (§ 191.14(c))

As stated in this subsection of the Assurance Requirements, the disposal site is to be designated by "the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location." The EPA assumes that, for as long as passive institutional controls endure and are understood, they can be effective in deterring systematic or persistent exploitation and can reduce the likelihood of inadvertent, intermittent human intrusion. However, passive institutional controls are not expected to eliminate the possibility of inadvertent human intrusion into the repository (U.S. EPA, 1985, p. 38088). Plans for passive institutional controls include markers warning of the presence of buried nuclear waste and identifying the boundaries of the controlled area, external records about the WIPP repository, and continued federal ownership.

The marker-development panel met in November 1991 and will meet again in January 1992. The panel will define characteristics for selecting and manufacturing markers and estimate the efficacy of these markers over the 10,000-year regulatory period. The panel will also provide estimates of the probabilistic performance of various types of markers. A consultant is preparing material that describes past efforts at developing barriers to human intrusion. An expert panel may be convened to further investigate this strategy.

Records will be preserved of the disposal site and its contents. An expert panel has not yet been planned on the types and possible content of external records that should be preserved. However, the expert panel on inadvertent human intrusion into the repository has estimated the effectiveness of records in preventing inadvertent human intrusion and suggested including specific information in external records on the potential effects of inadvertent exploratory drilling into the repository and techniques for plugging intrusion boreholes.

The Standard assumes that the DOE or some successor agency will retain ownership and administrative control over certain portions of the land around the WIPP. Withdrawal of the designated land to assure continued federal ownership has not been enacted.

10.2.4 MULTIPLE BARRIERS (§ 191.14(d))

This subsection of the Assurance Requirements specifies that different types of barriers, including engineered and natural barriers, be present in the repository to isolate the wastes from the accessible environment. At the WIPP, natural barriers include the salt formation and the geohydrologic setting. Engineered barriers include backfills and seals that isolate volumes of wastes. The effectiveness of these barriers will continue to be modeled in preliminary performance assessments until a determination is made that the barriers isolate the radioactive wastes to the levels required in the Standard.

The DOE has commissioned an Engineered Alternatives Task Force to evaluate possible additional engineering measures for the WIPP. Preliminary performance-assessment calculations indicate that modifications to the waste form that limit dissolution of radionuclides in brine have the potential to improve predicted performance of the repository (Marietta et al., 1989; Bertram-Howery and Swift, 1990). Current performance assessments are not complete enough to determine whether or not modifications will be needed for regulatory compliance. The 1991 performance-assessment calculations did not include simulations of possible alternatives. Selected alternatives will be examined in future performance-assessment calculations, however, to provide guidance to the DOE on possible effectiveness of modifications.

10.2.5 NATURAL RESOURCES (§ 191.14(e))

This subsection of the Assurance Requirements states that locations containing recoverable resources are not to be used for radioactive-waste repositories 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 summary report *Implementation of the Resource Disincentive in 40 CFR Part 191.14(e) at the Waste Isolation Pilot Plant* (U.S. DOE, 1991d) has been published.

The report addresses the issues of denial and attractiveness of hydrocarbon and potash resources, the most significant resources in the WIPP area. Studies indicate that hydrocarbon resources near the WIPP represent only a small percentage of U.S. and world supplies. The production of the potash mineral langbeinite, the only mineral resource in significant quantities within the WIPP boundaries and a source of potassium for use in the chemical and fertilizer industries, would only be slightly impacted by removing the area from mining operations. In addition, substitutes for the potassium sulfate in langbeinite are available. The *Final Environmental Impact Statement* (U.S. DOE, 1980a) and the *Final Supplement Environmental Impact Statement* (U.S. DOE, 1990c), among other reports, have indicated that, based on available information, the consequence of an inadvertent intrusion into the repository in search of resources is small. The report on the implementation of the resource disincentive (U.S. DOE, 1991d) states that the DOE believes that resource attractiveness does not appear to compromise the adequacy, safety, or reliability of the WIPP. Future studies will continue to evaluate the validity of this assumption.

10.2.6 WASTE REMOVAL (§ 191.14(f))

This subsection of the Assurance Requirements specifies that disposal systems are to be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal. The preamble to the Standard states that removal need not be easy or cheap, but merely possible (U.S. EPA, 1985, p. 38082). The WIPP Project has prepared a plan for waste removal during the operational phase (Subpart A of the Standard) based on the repository as designed. In addition, the EPA stated that current plans for mined geologic repositories meet this requirement without additional design (U.S. EPA, 1985, p. 38082). No further action for Subpart B of the Standard should be necessary.

10.3 Individual Protection Requirements (§ 191.15)

Repositories are expected to provide a reasonable expectation that, for 1,000 years after disposal, the undisturbed performance of the disposal system will not cause doses to any member of the public in the accessible environment to exceed certain levels. Previous and current evaluations of undisturbed performance at the WIPP have indicated no releases to the accessible environment within 10,000 years (Lappin et al., 1989; Marietta et al., 1989; Chapter 7 of this volume and Volume 2 of this report). The 1989 methodology demonstration reported that, for undisturbed performance, radionuclides did not reach the Culebra Dolomite within 50,000 years (Marietta et al., 1989). Gas generated within the waste panels was not directly included in the simulation for the 1991 preliminary performance calculations. However, the effects of gas generation were included indirectly by using elevated repository pressures calculated with a two-phase flow (gas and brine) computer program.

The compliance-assessment system for the WIPP must be used to predict releases to the accessible environment for undisturbed performance. Formal comparison to the Standard cannot be prepared until the bases of the system are judged adequate. However, analyses indicate that no releases will occur. Therefore, dose predictions are not expected to be required.

10.4 Groundwater Protection Requirements (§ 191.16)

The Groundwater Protection Requirements 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. Determining the presence of this type of groundwater relies on the definition of Class I groundwater, which is a groundwater resource that is 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. In addition, the groundwater must either be an irreplaceable source of drinking water, or the groundwater must be ecologically vital (U.S. EPA, 1984).

Studies have determined that no groundwater near the WIPP is highly vulnerable to contamination (U.S. DOE, 1989b; Lappin et al., 1989; Marietta et al., 1989; U.S. DOE, 1990f; Brinster, 1991). Groundwater flow in the Culebra Dolomite, the most transmissive hydrologic unit in the WIPP area, is generally to the south at a very slow rate, indicating that the area does not exhibit high hydraulic conductivity. Available data indicate that significant groundwater recharge does not occur near the WIPP.

Low yields from water-bearing units and high concentrations of total dissolved solids in groundwater near the WIPP severely limit groundwater use. Groundwater in the vicinity does not represent an irreplaceable source of drinking water for a substantial population. Groundwater at the WIPP does not support a particularly sensitive ecological system and, therefore, could not pollute a unique habitat.

Based on the 1985 Standard, the Groundwater Protection Requirements are not relevant to the WIPP disposal system. No further action should be necessary.

10.5 Formal Comparison to the Standard

The performance of the WIPP can be formally compared to the Standard when (U.S. DOE, 1990b)

the complete set of significant scenarios with probabilities of occurrence has been defined,

the compliance-assessment system is considered adequate, is operational, and has adequate documentation 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 components and processes identified by iterative uncertainty and sensitivity analyses, results of the in situ tests, and other appropriate refinements in the system. The utility of the compliance-assessment system is conditional on how well the disposal system is understood and is reflected here for the natural barriers of the controlled area and the engineered barriers of the repository/shaft 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) will be evaluated. If successive, iterative assessments converge to a stable CCDF, the performance assessment may be considered complete.

11. STATUS

This chapter summarizes the current status of the WIPP performance assessment and indicates where work can now be identified that remains to be done before a final comparison can be made to the Standard. The summary presented here is based on the preliminary results derived from the current modeling system and may change as subsequent performance-assessment iterations shift priorities for model development and data acquisition.

11.1 Current Status of the Compliance-Assessment System

The compliance-assessment system contains models used to estimate future performance of the disposal system and the data base that supports the models. Status of models and the data base are discussed in general terms separately and then summarized in detail for each component of the modeling system.

11.1.1 COMPLIANCE-ASSESSMENT MODELS

As discussed in Chapter 3, the models used in the WIPP performance assessment exist at four distinct levels. The status of the individual models can be considered separately at each of the four levels.

At the first level, a conceptual model is used to describe the processes to be simulated for a given performance measure. This model must be based on observational information and typically involves the application of a generalized knowledge of physical processes to the available information. Thus, a conceptual model provides a simplifying framework in which information can be organized and linked to processes that can be simulated with predictive models. Only rarely is a single conceptual model uniquely compatible with the observed data, although a conceptual model is sometimes sufficiently well-established that alternatives do not need to be considered in detail. In many cases, however, alternative conceptual models may be equally appropriate given the available information. For example, the current conceptual model used in performance-assessment simulations of regional groundwater flow in the Culebra Dolomite Member of the Rustler Formation includes recharge only to the north of the repository (see Chapter 5 of this volume). This is compatible with available well data, but it is not uniquely required by the data. Alternative conceptual models for the location of recharge to the system remain to be developed and tested.

At the second level, processes defined by the conceptual models are represented by mathematical models that can be used to predict behavior of the system through time. These mathematical models are typically systems of ordinary and partial differential equations. For example, the Darcy flow equations are used to represent the conceptual model for groundwater flow along a pressure gradient in a confined aquifer. Descriptions of the mathematical models used in the WIPP performance assessment are given in Volume 2 of this report.

At the third level, numerical models are developed that permit computational solutions that approximate the solutions of the mathematical models. In theory, this step is not always required in model development. In practice, however, it is unusual for a mathematical model based on differential equations to have a solution that can be determined without the use of an intermediate numerical model. Descriptions of the numerical solvers used in the WIPP performance assessment are given in the code manuals referenced in Volume 2 of this report.

At the fourth level, the numerical models must be translated to computer code to be implemented. A computer model could be no more than the encoding of a specific numerical model. In practice, however, computer programs typically contain options for a variety of numerical solutions for a single mathematical model and also may contain options for a variety of mathematical models corresponding to alternative conceptual models.

Ultimately, models used in the WIPP performance assessment must be verified and, to the extent possible, validated. Verification is the process by which a computer model is demonstrated to generate an acceptable numerical solution to the mathematical problem in question. For complex programs, verification is a nontrivial task and typically involves comparing benchmark test problem solutions with solutions generated by other codes and numerical models. Validation is the process by which a conceptual model and its associated mathematical model is demonstrated to provide an acceptable representation of reality. Some models can be validated experimentally. Others, however, particularly those that cover large domains with spatially varying properties and those that must simulate behavior for long time periods, are difficult to validate experimentally. In some cases, absolute validation may not be possible, and the final choice of a model will be based on subjective judgment.

11.1.2 THE COMPLIANCE-ASSESSMENT DATA BASE

The compliance-assessment data base serves two principal functions. First, it provides the essential basis for the conceptual models used to characterize the system. Conceptual models must explain the observed data. Second, the data base provides input to the computer models. Results of calculations depend directly on the data used to establish boundary conditions and parameter values, and uncertainty in model results depends directly on uncertainty in the values selected for the input parameters. The two functions of the data base are closely linked; for example, boundary conditions for computer models may be selected based directly on observed data or on values inferred for a particular conceptual model.

The status of the data base must be evaluated with respect to both functions. Is the currently available data adequate to support the conceptual model for a particular component of the system? Is the currently available data adequate for calculations, and can it be used to characterize the uncertainty in results? For both functions, the status of the data base is evaluated relative to the needs of the performance assessment. For example, some conceptual models may be adequately supported by sparse data, whereas for other components extensive data may remain insufficient to identify the best conceptual model. For some computer model parameters, large uncertainties may have little impact on estimated performance and therefore be acceptable; for other parameters even small uncertainties may result in large uncertainties in estimated performance.

11.1.3 SUMMARY OF THE STATUS OF THE COMPLIANCE-ASSESSMENT SYSTEM

The 1991 status of individual components within the compliance-assessment system is summarized in Table 11-1. Status is evaluated with respect to 40 CFR 191, Subpart B only. Similar evaluations have not been completed for status with respect to other regulations, including 40 CFR 268 and NEPA. Status is shown for the data base for each component, as determined by researchers within the WIPP Project. Status is also indicated for the performance-assessment module that corresponds to each component and that contains the conceptual models and the computer models with their encoded and numerical models. Qualifiers used to describe the status are "preliminary," "intermediate," and "advanced." These qualifiers refer to status relative to the needs of performance assessment, which, as noted above, may not coincide with the status relative to research on the specific topic. Thus, it is possible for a simplistic model or a sparse data base to be labeled "advanced" if uncertainty about the component in question has little impact on estimated performance. Alternatively, it is possible for sophisticated models and extensive data bases to be labeled "preliminary" if uncertainty about the component remains high and has a large impact on model results.

"Preliminary," where applied to the data base, indicates that data are insufficient to distinguish conceptual models or that data are not available for some important parameters. Where applied to conceptual models, "preliminary" means that the understanding of the component is incomplete and that alternative conceptual models may remain unidentified. Where

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B*, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
REPOSITORY/SHAFT/ BOREHOLE MODELS: REPOSITORY/SHAFT DESIGN			
Repository Design			
Geometry			Intermediate
Drift Backfill			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Panel/Drift Seals			
Concrete Seal Components			Intermediate
Grout Seal Components			Intermediate
Crushed Salt Seal Components			Intermediate
DRZ Seal Components (including fracture healing in salt)			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	
Shaft Seals			
Upper Shaft Sealing System			
Concrete Seal Components			Intermediate
Grout Seal Components			Intermediate
Clay Seal Components			Intermediate
Lower Shaft Sealing System			
Concrete Seal Components			Intermediate
Clay Seal Components			Intermediate
Crushed Salt Seal Components			Intermediate
DRZ Seal Components (including fracture healing in salt)			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	

* Status is evaluated with respect to 40 CFR 191, Subpart B only. Similar evaluations have not been completed for status with respect to other regulations, including 40 CFR 268 and NEPA.

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE (continued)

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
REPOSITORY/SHAFT/ BOREHOLE MODELS: PANEL MODEL			
Salado Formation			
Reference Stratigraphy			Advanced
Material Properties of Undisturbed Fm.			
Halite Absolute Permeability			Intermediate
Halite Pore Pressure			Intermediate
Anhydrite Absolute Permeability			Intermediate
Anhydrite Pore Pressure			Intermediate
Ideal Gas Solubility			Intermediate
Present Dissolved Gas Free in Fm.			Preliminary
Capillary Fingering			Preliminary
Enhanced H_2 Diffusion in Halite/Anhydrite			Preliminary
Material Properties of DRZ			
Halite Absolute Permeability			Intermediate
Halite Pore Pressure			Intermediate
Anhydrite Absolute Permeability			Preliminary
Anhydrite Pore Pressure			Preliminary
Porosity			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	
Waste/Backfill			
Composite Waste/Backfill Properties			
Effective Porosity			Intermediate
Absolute Permeability			Intermediate
Initial Saturation			Intermediate
Critical Shear Strength			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	
Properties of Backfill above Drums			
Effective Porosity			Intermediate
Absolute Permeability			Intermediate
Initial Saturation			Intermediate
Critical Shear Strength			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE (continued)

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
Inventory			
Combustibles			Intermediate
Metal/Glass			Intermediate
VOCs			Preliminary
Organics			Preliminary
Al & Fe & Heavy Metals			Preliminary
CH-Waste Inventory			Intermediate
RH-Waste Inventory			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	
40 CFR 191 Source Term			
Decay			Advanced
Solubility (laboratory tests)			Preliminary
Colloid Formation/Chelation (laboratory tests)			Preliminary
Retardation in Repository			Preliminary
Performance-Assessment Module	Preliminary	Preliminary	
Panel/Waste Interactions			
Gas Generation (laboratory tests)			
Generation Processes			
Corrosion			Intermediate
Biological			Preliminary
Radiolysis			Intermediate
Gas Gettering Processes			Intermediate
Coupling of Processes to Closure/Compaction, Brine/Gas Flow, and Gas Generation			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Brine/Gas Flow and Transport			
Relative Permeability (to gas)			
Undisturbed Anhydrite			Preliminary
Undisturbed Halite			Preliminary
DRZ Anhydrite			Preliminary
DRZ Halite			Preliminary
Waste/Backfill			Preliminary
Capillary Pressure			
Anhydrite			Preliminary
Halite			Preliminary
Threshold Pressure for Anhydrite Fracture Opening			Preliminary

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE (continued)

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
Brine/Gas Flow and Transport (continued)			
Gas Dissolved in Brine			
Initial			Preliminary
Potential			Intermediate
Radionuclide Transport in Salado			Preliminary
Performance-Assessment Module	Preliminary	Preliminary	
Creep Closure/Expansion			
Wall Closure			Advanced
Coupling With Gas Generation and Brine/Gas Flow			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Waste-Form and Backfill Compaction			
Waste Compaction			Intermediate
Coupling With Gas Generation and Brine/Gas Flow			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Human Intrusion[1]			
Material Properties of Borehole			
Drilling Properties			Advanced[2]
Plug Properties			Advanced[2]
Performance-Assessment Module	Advanced	Advanced	
Castile Brine Reservoir			
Areal Extent			Intermediate
Volume of Brine			Intermediate
Pressure			Intermediate
Permeability			Intermediate
Gas			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Intrusion Probability			Intermediate[3]
Performance-Assessment Module	Intermediate	Intermediate	

[1] Conditional on assumption of present-day drilling technology
[2] Adequacy controlled by regulation guidance
[3] Based on expert panel judgment and regulatory guidance

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE (continued)

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
GROUNDWATER FLOW AND TRANSPORT MODELS: GROUNDWATER FLOW MODEL			
Regional Hydrogeology			
3-D Regional Geology/Flow			
Understanding Present Flow			Intermediate
Predicting Future Flow			Preliminary
Climate Variability			Intermediate
Recharge Variability			
Present			Preliminary
Range in Future			Preliminary
Dissolution Processes			Intermediate
Integrate Geochemical/Isotopic Data			Intermediate
Performance-Assessment Module	Preliminary	Preliminary	
Local Hydrogeology			
2-D Groundwater (Culebra) Flow Model			
Boundary Conditions			
Present			Intermediate
Future			Intermediate
Transmissivity Distribution			
Definition of High T Zone			Intermediate
Uncertainty in T			Intermediate
Matrix/Fracture Porosity			Intermediate
Variable Brine Density Effects			
Flow Potential			Intermediate
Mixing			Preliminary
Effect of Potash Mining			Preliminary
Effect of Existing Boreholes			Preliminary
Performance-Assessment Module	Intermediate	Intermediate	
3-D Groundwater Flow Model			
Dewey Lake/Rustler Transmissivities			Preliminary
Dewey Lake/Rustler Boundary Conditions			
Vertical			Preliminary
Horizontal			Preliminary
Performance-Assessment Module	Preliminary	Preliminary	

TABLE 11-1. COMPLETENESS OF TECHNICAL BASES FOR PERFORMANCE ASSESSMENT WITH REGARD TO 40 CFR 191, SUBPART B, CONDITIONAL ON 1991 COMPLIANCE-ASSESSMENT SYSTEM AND AS-RECEIVED WASTE (concluded)

Compliance-Assessment System Component	Performance Assessment Understanding of Conceptual Model	Adequacy of Performance-Assessment Module	Adequacy of Data for Performance Assessment
GROUNDWATER FLOW AND TRANSPORT MODELS: RADIONUCLIDE TRANSPORT MODEL			
Physical Retardation			
Matrix Diffusion in Dual Porosity Transport			Intermediate
Performance-Assessment Module	Intermediate	Intermediate	
Chemical Retardation			
Radionuclide Solubility in Culebra Brine			Preliminary
Sorption by Clays			Preliminary
Performance-Assessment Module	Preliminary	Preliminary	
CUTTINGS MODELS: CUTTINGS/CAVINGS MODEL			
Drill Cuttings			
Performance-Assessment Module	Advanced[1]	Advanced[1]	
Erosion/Cavings			
Critical Shear Strength			Preliminary
Performance-Assessment Module	Preliminary	Intermediate	
Spalling			
Failure Criteria			Preliminary
Performance Assessment Module	Preliminary	Preliminary	

[1] Conditional on assumption of present-day drilling technology

applied to the performance-assessment modules, "preliminary" means work on one or more aspects of the mathematical, numerical, and computer models is either still in the planning stages or only recently initiated.

"Intermediate," where applied to the data base, means that data are sufficient for computations but that sources of uncertainty are not fully understood and uncertainty therefore has not been adequately quantified. Where applied to conceptual models, "intermediate" means that important processes are identified and understood and that significant alternative conceptual models, if any, may have been identified. Where applied to the performance-assessment modules, "intermediate" means that models are available, but that verification and validation are in the early stages and the application of the models to the WIPP performance assessment is still under development.

"Advanced," where applied to the data base, means that data for a specific component are fully adequate for performance assessments. Uncertainty is understood, quantified, and can be displayed in computational results. Where applied to conceptual models, "advanced" means that an appropriate conceptual model has been chosen and is adequately supported by the available data. Uncertainty in the conceptual model is adequately understood. Where applied to performance-assessment modules, "advanced" indicates validation and verification work is in progress and that the models are ready for use in performance assessments.

The status of the WIPP compliance-assessment system will change as the WIPP research and performance-assessment programs advance, and Table 11-1 will change accordingly in future iterations. 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 or module.

11.1.4 THE ROLE OF SENSITIVITY ANALYSES IN EVALUATING STATUS

Sensitivity analyses, as discussed in detail in Chapter 3 of this volume, provide information about the sensitivity of the modeling system to uncertainty in specific input parameters. For example, stepwise linear regression analyses can rank parameters in terms of the magnitude of the contribution to overall variability in modeled performance resulting from the variability in each parameter. These analyses are a useful tool for identifying those parameters where reductions in uncertainty (i.e., narrowing of the range of values from which the sample used in the Monte Carlo analysis is drawn) have the greatest potential to increase confidence in the estimate of disposal-system performance. Identification of sensitive parameters can help set priorities for resource allocation to allow the WIPP

Project to proceed as efficiently as possible toward a final evaluation of regulatory compliance. Sensitivity analyses performed as part of the 1990 preliminary comparison indicated that uncertainty in the values used for radionuclide solubility in the waste and retardation in the Culebra Dolomite Member dominated the variability in subsurface discharges to the accessible environment (Helton et al., 1991). As a result, expert panels were convened in 1991 to provide judgment on more suitable ranges and distributions for these parameters. Experimental programs have been accelerated for solubility and started for retardation to provide real data. However, additional research on a particular parameter will not invariably lead to a reduction in uncertainty. Reducing uncertainty in the data base is desirable, but in general the more important goal will be to determine the correct level of residual uncertainty that must be included in the analysis.

Sensitivity analyses are an important part of performance assessment, but because they are inherently conditional on the models, data distributions, and techniques used to generate them, they cannot provide insight about parameters not sampled, conceptual and computer models not used in the analysis in question, or processes that have been oversimplified during the sensitivity analyses. Qualitative judgment about the modeling system must be used in combination with sensitivity analyses to set priorities for performance-assessment data acquisition and model development.

REFERENCES

Adams, J. E. 1944. "Upper Permian Ochoa Series of Delaware Basin, West Texas and Southeastern New Mexico." *American Association of Petroleum Geologists Bulletin* **28**: 1596-1625.

Ahmed, S., D. R. Metcalf, and J. W. Pegram. 1981. "Uncertainty Propagation in Probabilistic Risk Assessment: A Comparative Study." *Nuclear Engineering and Design* **68**: 1-3.

Allen, D. M. 1971. *The Prediction Sum of Squares as a Criterion for Selecting Predictor Variables*. Report No. 23. Lexington, KY: Department of Statistics, University of Kentucky.

Anderson, R. Y. 1978. "Deep Dissolution of Salt, Northern Delaware Basin, New Mexico." Report to Sandia National Laboratories.

Anderson, R. Y. 1981. *Deep-Seated Salt Dissolution in the Delaware Basin, Texas and New Mexico*. New Mexico Geological Society Special Publication No. 10. 133-145.

Anderson, R. Y. 1983. "Evidence for Deep Dissolution in the Delaware Basin." Report prepared for the State of New Mexico Environmental Evaluation Group.

Andersson, J., T. Carlsson, T. Eng, F. Kautsky, E. Söderman, and S. Wingefors. 1989. *The Joint SKI/SKB Scenario Development Project*. TR89-35. Stockholm, Sweden: Svensk Kärnbränslehantering AB.

Apostolakis, G. 1990. "The Concept of Probability in Safety Assessments of Technological Systems." *Science* **250**: 1359-1364.

Apostolakis, G., R. Bras, L. Price, J. Valdes, K. Wahi, and E. Webb. 1991. *Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories*. NUREG/CR-3964. SAND86-0196/2. Washington DC: Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission.

Arthur D. Little, Inc. 1980. *Technical Support of Standards for High-Level Radioactive Waste Management, Volume D, Release Mechanisms*. EPA 520/4-79-007D. Washington, DC: U.S. Environmental Protection Agency.

Ash, R. B. 1972. *Real Analysis and Probability*. New York, NY: Academic Press.

Bachman, G. O. 1974. *Geologic Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico*. U.S. Geological Survey Open-File Report 74-194. Denver, CO: U.S. Geological Survey.

Bachman, G. O. 1980. *Regional Geology and Cenozoic History of the Pecos Region, Southeastern New Mexico*. U.S. Geological Survey Open-File Report D-77-946. Albuquerque, NM: U.S. Geological Survey.

Bachman, G. O. 1981. *Geology of Nash Draw, Eddy County, New Mexico.* U.S. Geological Survey Open-File Report 81-31.

Bachman, G. O. 1984. *Regional Geology of Ochoan Evaporites, Northern Part of the Delaware Basin.* New Mexico Bureau of Mines and Mineral Resources Circular 184. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Backman, G. O. 1985. *Assessment of Near-Surface Dissolution at and near the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico.* SAND84-7178. Albuquerque, NM: Sandia National Laboratories.

Bachman, G. O. 1987. *Karst in Evaporites in Southeastern New Mexico.* SAND86-7078. Albuquerque, NM: Sandia National Laboratories.

Barnett, V. 1982. *Comparative Statistical Inference (2nd Ed.).* New York, NY: Wiley.

Bates, R. L., and J. A. Jackson, eds. 1980. *Glossary of Geology.* 2nd ed. Falls Church, VA: American Geological Institute.

Beauheim, R. L. 1986. *Hydraulic-Test Results for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-1364. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L. 1987a. *Interpretations of Single-Well Hydraulic Tests Conducted At and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983-1987.* SAND87-0039. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L. 1987b. *Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-2311. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L. 1987c. *Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site.* SAND87-2456. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L. 1989. *Interpretation of H-11b4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site.* SAND89-0536. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L., and R. M. Holt, 1990. "Hydrogeology of the WIPP Site," in *Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico. Geological Society of America 1990 Annual Meeting Field Trip #14 Guidebook. Dallas, TX: The Dallas Geological Society. 131-180.*

Beauheim, R. L., G. J. Saulnier, Jr., and J. D. Avis. 1990. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND89-0536. Albuquerque, NM: Sandia National Laboratories.

Beauheim, R. L., G. J. Saulnier, Jr., and J. D. Avis. 1991. *Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report*. SAND90-0083. Albuquerque, NM: Sandia National Laboratories.

Belitz, K., and J. D. Bredehoeft. 1988. "Hydrodynamics of Denver Basin: Explanation of Subnormal Fluid Pressures." *American Association of Petroleum Geologists Bulletin* vol. 72, no. **11**: 1334-1359.

Bertram-Howery, S. G., and R. L. Hunter. 1989a. *Plans for Evaluation of the Waste Isolation Pilot Plant's Compliance with EPA Standards for Radioactive Waste Management and Disposal*. SAND88-2871. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and R. L. Hunter, eds. 1989b. *Preliminary Plan for Disposal-System Characterization and Long-Term Performance Evaluation of the Waste Isolation Pilot Plant*. SAND89-0178. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and P. N. Swift. 1990. *Status Report: Potential for Long-Term Isolation by the Waste Isolation Pilot Plant Disposal System.* SAND90-0616. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., M. G. Marietta, R. P. Rechard, P. N. Swift, D. R. Anderson, B. L. Baker, J. E. Bean, Jr., W. Beyeler, K. F. Brinster, R. V. Guzowski, J. C. Helton, R. D. McCurley, D. K. Rudeen, J. D. Schreiber, and P. Vaughn. 1990. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990*. SAND90-2347. Albuquerque, NM: Sandia National Laboratories.

Bingham, F. W., and G. E. Barr. 1979. *Scenarios for Long-Term Release of Radionuclides From a Nuclear-Waste Repository in the Los Medanos Region of New Mexico*. SAND78-1730. Albuquerque, NM: Sandia National Laboratories.

Bonano, E. J., and R. M. Cranwell. 1988. "Treatment of Uncertainties in the Performance Assessment of Geologic High-Level Radioactive Waste Repositories." *Mathematical Geology* **20**: 543-565.

Bonano, E. J., S. C. Hora, R. L. Keeney, and D. von Winterfeldt. 1989. *The Formal Use of Expert Judgments in Performance Assessment of Radioactive Waste Repositories*. SAND89-0495C, CONF-891008-1. Albuquerque, NM: Sandia National Laboratories.

Bonano, E. J., S. C. Hora, R. L. Keeney, and D. von Winterfeldt. 1990. *Elicitation and Use of Expert Judgement in Performance Assessment for High-Level Radioactive Waste Repositories*. NUREG/CR-5411, SAND89-1821. Albuquerque, NM: Sandia National Laboratories.

Bonilla, M. G. 1979. "Historic Surface Faulting--Map Patterns, Relation to Subsurface Faulting, and Relation to Preexisting Faults" in *Proceedings of Conference VIII, Analysis of Actual Fault Zones in Bedrock, April 1-5, 1979*. U.S. Geological Survey Open-File Report 79-1239: 36-65.

Borns, D. J. 1983. *Petrographic Study of Evaporite Deformation near the Waste Isolation Pilot Plant (WIPP)*. SAND83-0166. Albuquerque, NM: Sandia National Laboratories.

Borns, J. C., and S. E. Shaffer. 1985. *Regional Well-Log Correlation in the New Mexico Portion of the Delaware Basin*. SAND83-1798. Albuquerque, NM: Sandia National Laboratories.

Borns, D. J., and J. C. Stormont. 1988. *An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone*. SAND87-1375. Albuquerque, NM: Sandia National Laboratories.

Borns, D. J., and J. C. Stormont. 1989. "The Delineation of the Disturbed Rock Zone Surrounding Excavations in Salt." *Proceedings of the Rock Mechanics Symposium at the University of West Virginia, June 19-22, 1989*. Rotterdam, Netherlands: A.A. Balkema.

Borns, D. J., L. J. Barrows, D. W. Powers, and R. P. Snyder. 1983. *Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site*. SAND82-1069. Albuquerque, NM: Sandia National Laboratories.

Box, G. E. P., and N. R. Draper. 1987. *Empirical Model-Building and Response Surfaces*. New York, NY: Wiley.

Brausch, L. M., A. K. Kuhn, and J. K. Register. 1982. *Natural Resources Study, Waste Isolation Pilot Plant (WIPP), Eddy and Lea Counties, New Mexico*. WTSD-TME-3156. Albuquerque, NM: U.S. Department of Energy.

Bredehoeft, J. D. 1988. "Will Salt Repositories Be Dry?" *EOS*, American Geophysical Union, vol. 69, no. 9.

Breeding, R. J., J. C. Helton, W. B. Murfin, and L. N. Smith. 1990. *Evaluation of Severe Accident Risks: Surry Unit 1*. NUREG/CR-4551, SAND86-1309, vol. 3, rev. 1. Albuquerque, NM: Sandia National Laboratories.

Brinster, K. F. 1991. *Preliminary Geohydrologic Conceptual Model of the Los Medaños Region near the Waste Isolation Pilot Plant for the Purpose of Performance Assessment*. SAND89-7147. Albuquerque, NM: Sandia National Laboratories.

Brush, L. H., and D. R. Anderson. 1988a. "Appendix A.1: Drum (Metal) Corrosion, Microbial Decomposition of Cellulose, Reactions Between Drum-Corrosion Products and Microbially Generated Gases, Reactions Between Possible Backfill Constituents and Gases and Water Chemical Reactions" in *System Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico, March, 1989*. Eds. A. R. Lappin, R. L. Hunter, D. P. Garber, and P. B. Davies. SAND89-0462. Albuquerque, NM: Sandia National Laboratories.

Brush, L. H., and D. R. Anderson. 1988b. "Appendix A.2: Effects of Microbial Activity on Repository Chemistry, Radionuclide Speciation, and Solubilities in WIPP Brines" in *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; March 1989*. Eds. A. R. Lappin, R. L. Hunter, D. P. Garber, and P. B. Davies. SAND89-0462. Albuquerque, NM: Sandia National Laboratories.

Brush, L. H., and D. R. Anderson. 1989. "Appendix E: Estimates of Radionuclide Concentrations in Brines" in *Performance Assessment Methodology Demonstration: Methodology Development for Purposes of Evaluating Compliance with EPA 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant*. M. G. Marietta, S. G. Bertram-Howery, D. R. Anderson, K. Brinster, R. Guzowski, H. Iuzzolino, and R. P. Rechard. SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

Burkholder, H. C. 1980. "Waste Isolation Performance Assessment--A Status Report" in *Scientific Basis for Nuclear Waste Management*. Volume 2. Plenum Press. 689-702.

Burns, J. R. 1975. "Error Analysis of Nonlinear Simulations: Applications to World Dynamics." *IEEE Transactions on Systems, Man, and Cybernetics* SMC-5: 331-340.

Butcher, B. M. 1989. *Waste Isolation Pilot Plant Simulated Waste Compositions and Mechanical Properties*. SAND89-0372. Albuquerque, NM: Sandia National Laboratories.

Butcher, B. M. 1990. *Preliminary Evaluation of Potential Engineered Modifications for the Waste Isolation Pilot Plant (WIPP)*. SAND89-3095. Albuquerque, NM: Sandia National Laboratories.

Butcher, B. M. 1991. *The Advantages of a Salt/Bentonite Backfill for Waste Isolation Pilot Plant Disposal Rooms*. SAND90-3074. Albuquerque, NM: Sandia National Laboratories.

Cacuci, D. G. 1981a. "Sensitivity Theory for Nonlinear Systems. I. Nonlinear Functional Analysis Approach." *Journal of Mathematical Physics* **22**: 2794-2802.

Cacuci, D. G. 1981b. "Sensitivity Theory for Nonlinear Systems. II. Extensions to Additional Classes of Responses." *Journal of Mathematical Physics* **22**: 2803-2812.

Cacuci, D. G., C. F. Weber, E. M. Oblow, and J. H. Marable. 1980. "Sensitivity Theory for General Systems of Nonlinear Equations." *Nuclear Science and Engineering* **75**: 88-110.

Campbell, J. E., and R. M. Cranwell. 1988. "Performance Assessment of Radioactive Waste Repositories." *Science* **239**: 1389-1392.

Campbell, J. E., and D. E. Longsine. 1990. "Application of Generic Risk Assessment Software to Radioactive Waste Disposal." *Reliability Engineering and System Safety* 30: 183-193.

Cauffman, T. L., A. M. LaVenue, and J. P. McCord. 1990. *Ground-Water Flow Modeling of the Culebra Dolomite: Volume II - Data Base.* SAND89-7068/2. Albuquerque, NM: Sandia National Laboratories.

Chapman, J. B. 1986. *Stable Isotopes in the Southeastern New Mexico Groundwater: Implications for Dating Recharge in the WIPP Area.* EEG-35. Santa Fe, NM: New Mexico Environmental Evaluation Group.

Chapman, J. B. 1988. *Chemical and Radiochemical Characteristics of Groundwater in the Culebra Dolomite, Southeastern New Mexico.* EEG-39. Santa Fe, NM: Environmental Evaluation Group, Environmental Improvement Division, Health and Environment Department, State of New Mexico.

Cheeseman, R. J. 1978. *Geology and Oil/Potash Resources of the Delaware Basin, Eddy and Lea Counties, New Mexico.* New Mexico Bureau of Mines and Mineral Resources Circular 159. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 7-14.

Chen, X., and N. C. Lind. 1983. "Fast Probability Integration by Three Parameter Normal Tail Approximation." *Structural Safety* **1**: 169-176.

Cheng, R. C. H., and T. C. Iles. 1983. "Confidence Bounds for Cumulative Distribution Functions of Continuous Random Variables." *Technometrics* **25**: 77-86.

Claiborne, H. C., and F. Gera. 1974. *Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico.* ORNL-TM-4639. Oak Ridge, TN: Oak Ridge National Laboratory.

COHMAP (Cooperative Holocene Mapping Project) members. 1988. "Climatic Changes of the Last 18,000 years: Observations and Model Simulations." *Science* **241**: 1043-1052.

Cole, F. W. 1975. *Introduction to Meteorology Second Edition.* New York, NY: John Wiley and Sons, Inc.

Conover, W. J. 1980. *Practical Nonparametric Statistics* (2nd ed.). New York, NY: Wiley.

Cook, I., and S. D. Unwin. 1986. "Controlling Principles for Prior Probability Assignments in Nuclear Risk Assessment." *Nuclear Science and Engineering* **94**: 107-119.

Cooper, J. B., and V. M. Glanzman. 1971. "Geohydrology of Project GNOME Site, Eddy County, New Mexico" in *Hydrology of Nuclear Test Sites,* U.S. Geological Survey Professional Paper 712-A.

Cox, D. C., and P. Baybutt. 1981. "Methods for Uncertainty Analysis: A Comparative Survey." *Risk Analysis* **1**: 251-258.

Cox, N. D. 1977. "Comparison of Two Uncertainty Analysis Methods." *Nuclear Science and Engineering* **64**: 258-265.

Cranwell, R. M., J. E. Campbell, J. C. Helton, R. L. Iman, D. E. Longsine, N. R. Ortiz, G. E. Runkle, and M. J. Shortencarier. 1987. *Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report*. NUREG/CR-2452, SAND81-2573. Albuquerque, NM: Sandia National Laboratories.

Cranwell, R. M., R. V. Guzowski, J. E. Campbell, and N. R. Ortiz. 1990. *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure*. NUREG/CR-1667, SAND80-1429. Albuquerque, NM: Sandia National Laboratories.

Cukier, R. I., C. M. Fortuin, K. E. Shuler, A. G. Petschek, and J. H. Schiably. 1973. "Study of the Sensitivity of Coupled Reaction Systems to Uncertainties in Rate Coefficients, I. Theory." *Journal of Chemical Physics* **59**: 3873-3878.

Cukier, R. I., H. B. Levine, and K. K. Shuler. 1978. "Nonlinear Sensitivity Analysis of Multiparameter Model Systems." *Journal of Computational Physics* **26**: 1-42.

Davies, P. B. 1983. "Assessing the Potential for Deep-Seated Salt Dissolution and the Subsidence at the Waste Isolation Pilot Plant (WIPP)." Unpublished manuscript presented at the State of New Mexico Environmental Evaluation Group conference, WIPP Site Suitability for Radioactive Waste Disposal, Carlsbad, NM, May 12-13, 1983.

Davies, P. B. 1984. "Deep-Seated Dissolution and Subsidence in Bedded Salt Deposits." Ph.D. dissertation. Dept. of Applied Earth Sciences, Stanford University.

Davies, P. B. 1989. *Variable-Density Ground-Water Flow and Paleohydrology in the Region Surrounding the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico*. U.S. Geological Survey Open-File Report 88-490. Albuquerque, NM: U.S. Geological Survey.

Dickinson, R. P., and R. J. Gelinas. 1976. "Sensitivity Analysis of Ordinary Differential Equation Systems - A Direct Method." *Journal of Computational Physics* **21**: 123-143.

Doctor, P. G. 1989. "Sensitivity and Uncertainty Analyses for Performance Assessment Modeling." *Engineering Geology* **26**: 411-429.

Doctor, P. G., E. A. Jackson, and J. A. Buchanan. 1988. *A Comparison of Uncertainty Analysis Methods Using a Groundwater Flow Model*. PNL-5649. Richland, WA: Pacific Northwest Laboratory.

Dougherty, E. P., and H. Rabitz. 1979. "A Computational Algorithm for the Green's Function Method of Sensitivity Analysis in Chemical Kinetics." *International Journal of Chemical Kinetics* **11**: 1237-1248.

Dougherty, E. P., J. T. Hwang, and H. Rabitz. 1979. "Further Developments and Applications of the Green's Function Method of Sensitivity Analysis in Chemical Kinetics." *Journal of Chemical Physics* **71**: 1794-1808.

Downing, D. J., R. H. Gardner, and F. O. Hoffman. 1985. "An Examination of Response-Surface Methodologies for Uncertainty Analysis in Assessment Models." *Technometrics* **27**: 151-163.

Draper, N. R., and H. Smith. 1981. *Applied Regression Analysis, Second Edition*. New York, NY: Wiley.

Drez, P. 1989. "Preliminary Nonradionuclide Inventory of CH-TRU Waste," letter from Paul Drez, International Technology Corporation, Albuquerque, NM, to Larry Brush, Sandia National Laboratories, Albuquerque, NM.

Earth Technology Corporation. 1988. *Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP Site*. SAND87-7144. Albuquerque, NM: Sandia National Laboratories.

EPRI (Electric Power Research Institute). 1989. *Probabilistic Seismic Hazard Evaluations at Nuclear Plant Sites in the Central and Eastern United States: Resolution of the Charleston Earthquake Issue*. EPRI-NP-6395D. Palo Alto, CA: EPRI.

Fanchi, J. R., J. E. Kennedy, and D. L. Dauben. 1987. *BOAST II: A Three-Dimensional Three-Phase Black Oil Applied Simulation Tool*. DOE/BC-88/2/SP, DE 88001205. U.S. Department of Energy.

Fedra, K. 1983. *Environmental Modeling under Uncertainty: Monte Carlo Simulation*. RR-83-28. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Feller, W. 1971. *An Introduction to Probability Theory and Its Applications*, *Vol. II* (2nd Ed.). New York, NY: Wiley.

Fischer, F., and J. Ehrhardt. 1985. *Uncertainty Analysis with a View Towards Applications in Accident Consequence Assessments*. KfK 3906. Karlsruhe, FRD: Kernforschungszentrum Karlsruhe.

Frank, P. M. 1978. *Introduction to System Sensitivity Theory*. New York: Academic Press.

Gardner, R. H., and R. V. O'Neill. 1983. "Parameter Uncertainty and Model Predictions: A Review of Monte Carlo Results." *Uncertainty and Forecasting of Water Quality*. Eds. M. B. Beck and G. Van Straten. New York: Springer-Verlag. 245-257.

Gardner, R. H., R. V. O'Neill, J. B. Mankin, and J. H. Carney. 1981. "A Comparison of Sensitivity Analysis and Error Analysis Based on a Stream Ecosystem Model." *Ecological Modelling* 12: 173-190.

Geohydrology Associates, Inc. 1979. *Water-Resources Study of the Carlsbad Potash Area, New Mexico*. Consultant Report for the U.S. BLM. Contract No. YA-S12-CT8-195.

Geological Society of America. 1984. *Decade of North American Geology Geologic Time Scale*. Geological Society of America Map and Chart Series MCH050.

Gibbons, A. 1990. "Growing Crops in Saltwater." *Science* **248**: 963.

Gilkey, A. P. 1986a. *SPLOT-A Distance-Versus-Variable Plot Program for the Output of a Finite Element Analysis*. SAND86-0882. Albuquerque, NM: Sandia National Laboratories.

Gilkey, A. P. 1986b. *TPLOT-A Time History or X-Y Plot Program for the Output of a Finite Element Analysis*. SAND86-0882. Albuquerque, NM: Sandia National Laboratories.

Gilkey, A. P., and D. P. Flanagan. 1987. *DETOUR-A Deformed Mesh/Contour Plot Program*. SAND86-0914. Albuquerque, NM: Sandia National Laboratories.

Gussow, W. C. 1968. "Salt Diapirism: Importance of Temperature, and Energy Source of Displacement in Diapirism and Diapirs." *American Association of Petroleum Geologists Memoir 8*, no. **8**: 16-52.

Guzowski, R. V. 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-7149. Albuquerque, NM: Sandia National Laboratories.

Guzowski, R. V. 1991. *Evaluation of Applicability of Probability Techniques to Determining the Probability of Occurrence of Potentially Disruptive Intrusive Events at the Waste Isolation Pilot Plant*. SAND90-7100. Albuquerque, NM: Sandia National Laboratories.

Halbouty, M. T. 1979. *Salt Domes. Gulf Region, United States & Mexico*. 2nd ed. Houston, TX: Gulf Publishing Company.

Hale, W. E., and A. Clebsch, Jr. 1958. *Preliminary Appraisal of Groundwater Conditions in Southeastern Eddy County and Southwestern Lea County, New Mexico*. U.S. Geological Survey Trace Element Memorandum Report 1045. 23.

Hale, W. E., L. S. Hughes, and E. R. Cox. 1954. *Possible Improvement of Quality of Water of the Pecos River by Diversion of Brine at Malaga Bend, Eddy County, New Mexico*. Carlsbad, NM: Pecos River Commission, New Mexico and Texas, in cooperation with USGS Water Resources Division.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russell. 1988. "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model." *Journal of Geophysical Research* **93**: 9341-9364.

Harms, J. C., and C. R. Williamson. 1988. "Deep-Water Density Current Deposits of Delaware Mountain Group (Permian), Delaware Basin, Texas and New Mexico." *American Association of Petroleum Geologists Bulletin* **72**: 299-317.

Harper, W. V., and S. K. Gupta. 1983. *Sensitivity/Uncertainty Analysis of a Borehole Scenario Comparing Latin Hypercube Sampling and Deterministic Sensitivity Approaches*. BMI/ONWI-516. Columbus, OH: Battelle Memorial Institute.

Harper, F. T. et al., 1990. *Evaluation of Severe Accident Risks: Quantification of Major Input Parameters; Experts' Determination of In-Vessel Issues*. NUREG/CR-4551, SAND86-1309, vol. 2, part 1, rev. 1. Albuquerque, NM: Sandia National Laboratories.

Harper, F. T. et al., 1991. *Evaluation of Severe Accident Risks: Quantification of Major Input Parameters; Experts' Determination of Containment Loads and Molten Core-Concrete Issues*. NUREG/CR-4551, SAND86-1309 vol 2, part 2, rev. 1. Albuquerque, NM: Sandia National Laboratories.

Hartmann, W. K. 1979. "Long-Term Meteorite Hazards to Buried Nuclear Waste. Report 2" in *A Summary of FY-1978 Consultant Input for Scenario Methodology Development*. Pacific Northwest Laboratories. PNL-2851: VI-1-VI-15.

Haug, A., V. A. Kelley, A. M. LaVenue, and J. F. Pickens. 1987. *Modeling of Groundwater Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site: Interim Report*. SAND86-7167. Albuquerque, NM: Sandia National Laboratories.

Havens, J. S., and D. W. Wilkins. 1979. *Experimental salinity alleviation at Malaga Bend of the Pecos River, Eddy County, New Mexico*. U.S. Geological Survey Water-Resources Investigations 80-4.

Hayes, P. T. 1964. *Geology of the Guadalupe Mountains, New Mexico*. U.S. Geological Survey Professional Paper 446.

Hays, J. D., J. Imbrie, and N. J. Shackleton. 1976. "Variations in the Earth's Orbit; Pacemaker of the Ice Ages." *Science* **194**: 1121-1132.

Helton, J. C., R. L. Iman, and J. B. Brown. 1985. "Sensitivity Analysis of the Asymptotic Behavior of a Model for the Environmental Movement of Radionuclides." *Ecological Modelling* **28**: 243-278.

Helton, J. C., R. L. Iman, J. D. Johnson, and C. D. Leigh. 1986. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics." *Nuclear Technology* **73**: 320-342.

Helton, J. C., J. M. Griesmeyer, F. E. Haskin, R. L. Iman, C. N. Amos, and W. B. Murfin. 1988. "Integration of the NUREG-1150 Analyses: Calculation of Risk and Propagation of Uncertainties." *Proceedings of the Fifteenth Water Reactor Safety Research Information Meeting*: pp. 151-176. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Helton, J. C., R. L. Iman, J. D. Johnson, and C. D. Leigh. 1989. "Uncertainty and Sensitivity Analysis of a Dry Containment Test Problem for the MAEROS Aerosol Model." *Nuclear Science and Engineering* **102**: 22-42.

Helton, J. C., J. W. Garner, R. D. McCurley, and D. K. Rudeen. 1991. *Sensitivity Analysis Techniques and Results for Performance Assessment at the Waste Isolation Pilot Plant*. SAND90-7103. Albuquerque, NM: Sandia National Laboratories.

Hendrickson, R. G. 1984. *Survey of Sensitivity Analysis Methodology*. NBSIR 84-2814. Washington, D. C.: U.S. National Bureau of Standards.

Hendry, D. F. 1984. "Monte Carlo Experimentation in Econometrics," in Z. Groiliches and M. D. Intriligator (eds.), *Handbook of Econometrics, vol. II: 937-976*. New York, NY: Elsevier.

Hills, J. M. 1984. "Sedimentation, Tectonism, and Hydrocarbon Generation in the Delaware Basin, West Texas and Southeastern New Mexico." *American Association of Petroleum Geologists Bulletin* **68**: 250-267.

Hiss, W. L. 1975. "Stratigraphy and Ground-Water Hydrology of the Capitan Aquifer, Southeastern New Mexico and West Texas." Ph.D. dissertation. University of Colorado, Boulder, CO.

Holmes, R. W. 1987. "Uncertainty Analysis for the Long-Term Assessment of Uranium Mill Tailings" in *Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems*, 167-190. Paris: Organization for Economic Co-Operation and Development.

Holt, R. M., and D. W. Powers. 1988. *Facies Variability and Post-Depositional Alteration Within the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico*. DOE/WIPP-88-004. Carlsbad, NM: U.S. Department of Energy.

Hora, S. C., and R. L. Iman. 1989. "Expert Opinion in Risk Analysis: The NUREG-1150 Methodology." *Nuclear Science and Engineering* **102**: 323-331.

Hora, S. C., D. von Winterfeldt, and K. M. Trauth. 1991. *Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*. SAND90-3063. Albuquerque, NM: Sandia National Laboratories.

Houghton, J. T., G. J. Jenkins, and J. J. Ephraums. 1990. *Climate Change: The IPCC Scientific Assessment*. Cambridge, UK: Cambridge University Press.

Hunter, R. L. 1983. *Preliminary Scenarios for the Release of Radioactive Waste From a Hypothetical Repository in Basalt of the Columbia Plateau*. NUREG/CR-3353, SAND83-1342. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L. 1985. *A Regional Water Balance for the Waste Isolation Pilot Plant (WIPP) Site and Surrounding Area*. SAND84-2233. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L. 1989. *Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-2546. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L., G. E. Barr, and F. W. Bingham. 1982. *Preliminary Scenarios for Consequence Assessments of Radioactive-Waste Repositories at the Nevada Test Site*. SAND82-0426. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L., G. E. Barr, and F. W. Bingham. 1983. *Scenarios for Consequence Assessments of Radioactive-Waste Repositories at Yucca Mountain, Nevada Test Site*. SAND82-1277. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L., R. M. Cranwell, and M. S. Y. Chu. 1986. *Assessing Compliance with the EPA High-Level Waste Standard: An Overview*. SAND86-0121, NUREG/CR-4510. Albuquerque, NM: Sandia National Laboratories.

Huyakorn, P. S., H. O. White, Jr., and S. Panday. 1989. *STAFF2D Solute Transport and Fracture Flow in Two Dimensions*. Herndon, VA: Hydrogeologic, Inc.

Hwang, J. T., E. P. Dougherty, S. Rabitz, and H. Rabitz. 1978. "The Green's Function Method of Sensitivity Analysis in Chemical Kinetics." *Journal of Chemical Physics* **69**: 5180-5191.

IAEA (International Atomic Energy Agency). 1983. *Concepts and Examples of Safety Analyses for Radioactive Waste Repositories in Continental Geological Formations*. Safety Series No. 50. Paris: International Atomic Energy Agency.

IAEA (International Atomic Energy Agency). 1989. *Evaluating the Reliability of Predictions Made Using Environmental Transfer Models*. Safety Series Report No. 100. Vienna: International Atomic Energy Agency.

Ibrekk, H., and M. G. Morgan. 1987. "Graphical Communication of Uncertain Quantities to Nontechnical People." *Risk Analysis* **7**: 519-529.

ICBO (International Conference of Building Officials). 1979. *Uniform Building Code*. Whittier, CA: International Conference of Building Officials.

ICRP (International Commission on Radiological Protection). 1959. *Report of the ICRP Committee II on Permissible Dose for Internal Radiation*. ICRP Publication 2. Pergamon Press.

Iman, R. L., 1981. "Statistical Methods for Including Uncertainty Associated with the Geologic Isolation of Radioactive Waste Which Allow For a Comparison with Licensing Criteria" in *Proceedings of the Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High-Level Radioactive Waste, Gatlinburg, TN, March 9-13 1981*.

Iman, R. L. 1982. "Statistical Methods for Including Uncertainties Associated with Geologic Isolation of Radioactive Waste Which Allow for a Comparison with Licensing Criteria," in *Proceedings of the Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High Level Radioactive Waste, Gatlinburg, TN March 9-13, 1981*. D. C. Hocher, ed. NUREG/CP-0022, CONF-810372: 145-157. Oak Ridge, TN: Oak Ridge National Laboratory.

Iman, R. L., and W. J. Conover. 1979. "The Use of the Rank Transform in Regression." *Technometrics* **21**: 499-509.

Iman, R. L., and W. J. Conover. 1980a. "Small Sample Sensitivity Analysis Techniques for Computer Models, with an Application to Risk Assessment." *Communications in Statistics* **A9**: 1749-1842.

Iman, R. L., and W. J. Conover. 1980b. "Rejoinder to Comments." *Communications in Statistics* **A9**: 1863-1874.

Iman, R. L., and W. J. Conover. 1982a. *Sensitivity Analysis Techniques: Self-Teaching Curriculum*. SAND81-1978, NUREG/CR-2350. Albuquerque, NM: Sandia National Laboratories.

Iman, R. L., and W. J. Conover. 1982b. "A Distribution-Free Approach to Inducing Rank Correlation Among Input Variables." *Communications in Statistics*, vol. B11, no. 3: 311-334.

Iman, R. L., and W. J. Conover. 1983. *A Modem Approach to Statistics*. New York: Wiley.

Iman, R. L., and J. M. Davenport. 1982. "Rank Correlation Plots for Use with Correlated Input Variables." *Communications in Statistics B11* **11**: 335-360.

Iman, R. L., and J. C. Helton. 1985a. *A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models*. NUREG/CR-3904, SAND84-1461. Albuquerque, NM: Sandia National Laboratories.

Iman, R. L. and J. C. Helton. 1985b. "Overview of Methods for Uncertainty Analysis and Sensitivity Analysis in Probabilistic Risk Assessment" in *Proceedings of the ANS/ENS International Topical Meeting on Probabilistic Safety Methods and Applications, San Francisco, CA, USA, 24 February - 1 March 1985*, vol. 1, pp. 15-1 to 15-11. La Grange Park, IL: American Nuclear Society.

Iman, R. L., and J. C. Helton. 1988. "An Investigation of Uncertainty and Sensitivity Analysis Techniques for Computer Models." *Risk Analysis* **8**: 71-90.

Iman, R. L. and J. C. Helton. 1991. "The Repeatability of Uncertainty and Sensitivity Analyses For Complex Probabilistic Risk Assessments." *Risk Analysis*. In press (December).

Iman, R. L., J. C. Helton, and J. E. Campbell. 1978. *Risk Methodology for Geologic Disposal of Radioactive Waste: Sensitivity Analysis Techniques.* NUREG/CR-0394, SAND78-0912. Albuquerque, NM: Sandia National Laboratories.

Iman, R. L., J. C. Helton, and J. E. Campbell. 1981a. "An Approach to Sensitivity Analysis of Computer Models, Part 1. Introduction, Input Variable Selection and Preliminary Variable Assessment." *Journal of Quality Technology* **13**: 174-183.

Iman, R. L., J. C. Helton, and J. E. Campbell. 1981b. "An Approach to Sensitivity Analysis of Computer Models, Part 2. Ranking of Input Variables, Response Surface Validation, Distribution Effect and Technique Synopsis." *Journal of Quality Technology* **13**: 232-240.

Iman, R. L., M. J. Shortencarier, and J. D. Johnson. 1985. *A FORTRAN 77 Program and User's Guide for the Calculation of Partial Correlation and Standardized Regression Coefficients.* NUREG/CR-4122, SAND85-0044. Albuquerque, NM: Sandia National Laboratories.

Imbrie, J. 1985. "A Theoretical Framework for the Pleistocene Ice Ages." *Journal of the Geological Society of London* **142**: 417-432.

Imbrie, J., and J. Z. Imbrie. 1980. "Modeling the Climatic Response to Orbital Variations." *Science* **207**. 943-953.

Imbrie, J., J. D. Hays, D. G. Martinson, et al. 1984. "The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine ^{18}O Record." *Milankovitch and Climate.* Eds. A. L. Berger et al. Boston, MA: D. Reidel. 269-305.

Jacobson, E. A., M. D. Freshley, and F. H. Dove. 1985. *Investigations of Sensitivity and Uncertainty in Some Hydrologic Models of Yucca Mountain and Vicinity.* SAND84-7212. Albuquerque, NM: Sandia National Laboratories.

Jones, C. L. 1978. *Test Drilling for Potash Resources: Waste Isolation Pilot Plant Site, Eddy County, New Mexico.* U.S. Geological Survey Open-File Report 78-592. Washington, DC: U.S. Geological Survey.

Kaplan, S., and B. J. Garrick. 1981. "On the Quantitative Definition of Risk." *Risk Analysis* 1: 11-27.

Karnbranslesakerhet. 1978. *Handling of Spent Nuclear Fuel and Final Storage of Vitrified High-Level Reprocessing Waste.* Stockholm, Sweden: Karnbranslesakerhet.

Keesey, J. J. 1976. *Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Storage Site, Eddy County, New Mexico.* 2 volumes. Midland, TX: Sipes, Williamson and Aycock.

Keesey, J. J. 1979. *Evaluation of Directional Drilling for Oil and Gas Reserves Underlying the WIPP Site Area, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson and Associates.

Kelly, V. A., and J. F. Pickens. 1986. *Interpretation of the Convergent-Flow Tracer Tests Conducted in the Culebra Dolomite at the H-3 and H-4 Hydropads at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-7161. Albuquerque, NM: Sandia National Laboratories.

Kelly, V. A., and G. J. Saulnier, Jr. 1990. *Core Analysis From the Culebra Dolomite at the Waste Isolation Pilot Plant.* SAND90-7011. Albuquerque, NM: Sandia National Laboratories.

Kim, T. W., S. H. Chang, and B. H. Lee. 1988a. "Uncertainty and Sensitivity Analyses in Evaluating Risk of High Level Waste Repository." *Radioactive Waste Management and the Nuclear Fuel Cycle* **10**: 321-356.

Kim, T. W., S. H. Chang, and B. H. Lee. 1988b. "Comparative Study on Uncertainty and Sensitivity Analysis and Application to LOCA Model." *Reliability Engineering and System Safety* **21**: 1-26.

Kleijnen, J. P. C. 1974. *Statistical Techniques in Simulation,* Parts 1 and 2. New York, NY: Marcel Dekker.

Kleijnen, J. P. C. 1987. *Statistical Tools for Simulation Practitioners.* New York, NY: Marcel Dekker.

Kunkler, J. L. 1980. *Evaluation of the Malaga Bend Salinity Alleviation Project Eddy County, New Mexico.* U.S. Geological Survey Open-File Report 80-1111. Albuquerque, NM: U.S. Geological Survey/Water Resources Division and the Pecos River Commission.

Lambert, S. J. 1983. *Dissolution of Evaporites in and around the Delaware Basin, Southeastern New Mexico and West Texas.* SAND82-0461. Albuquerque, NM: Sandia National Laboratories.

Lambert, S. J. 1991. "Isotopic Constraints on the Rustler and Dewey Lake Groundwater Systems," Chapter 5 in *Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico.* M. D. Siegel, S. J. Lambert, and K. L. Robinson, eds. SAND88-0196. Albuquerque, NM: Sandia National Laboratories.

Lambert, S. J., and J. A. Carter. 1984. *Uranium-Isotope Disequilibrium in Brine Reservoirs of the Castile Fm., Northern Delaware Basin, Southeastern New Mexico, I: Principles and Methods.* SAND83-0144. Albuquerque, NM: Sandia National Laboratories.

Lambert, S. J., and J. A. Carter. 1987. *Uranium-Isotope Systematics in Groundwaters of the Rustler Formation, Northern Delaware Basin, Southeastern New Mexico.* SAND87-0388. Albuquerque, NM: Sandia National Laboratories.

Lambert, S. J., and D. M. Harvey. 1987. *Stable-Isotope Geochemistry of Groundwater in the Delaware Basin of Southeastern New Mexico.* SAND87-0138. Albuquerque, NM: Sandia National Laboratories.

Lambert, S. J., and J. W. Mercer. 1978. *Hydrologic Investigations of the Los Medaños Area, Southeastern New Mexico, 1977.* SAND77-1401. Albuquerque, NM: Sandia National Laboratories.

Lappin, A. R. 1988. *Summary of Site-Characterization Studies Conducted from 1983 through 1987 at the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* SAND88-0157. Albuquerque, NM: Sandia National Laboratories.

Lappin, A. R., R. L. Hunter, D. P. Garber, P. B. Davies, R. L. Beauheim, D. J. Borns, L. H. Brush, B. M. Butcher, T. Cauffman, M. S. Y. Chu, L. S. Gomez, R. V. Guzowski, H. J. Iuzzolino, V. Kelley, S. J. Lambert, M. G. Marietta, J. W. Mercer, E. J. Nowak, J. Pickens, R. P. Rechard, M. Reeves, K. L. Robinson, and M. D. Siegel. 1989. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; March 1989.* SAND89-0462. Albuquerque, NM: Sandia National Laboratories.

Lappin, A. R., R. L. Hunter, P. B. Davies, D. J. Borns, M. Reeves, J. Pickens, and H. J. Iuzzolino. 1990. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; September, 1989.* SAND89-1996. Albuquerque, NM: Sandia National Laboratories.

LaVenue, A. M., A. Haug, and V. A. Kelley. 1988. *Numerical Simulation of Groundwater Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site; Second Interim Report.* SAND88-7002. Albuquerque, NM: Sandia National Laboratories.

LaVenue, A. M., T. L. Cauffman, and J. F. Pickens. 1990. *Ground-Water Flow Modeling of the Culebra Dolomite: Volume 1 - Model Calibration.* SAND89-7068. Albuquerque, NM: Sandia National Laboratories.

Lee, F. T., and J. F. Abel, Jr. 1983. *Subsidence from Underground Mining: Environmental Analysis and Planning Considerations.* Circular 876. U. S. Geological Survey.

Levin, R. D., and M. Tribus, eds. 1978. *The Maximum Entropy Formalism.* Cambridge, MA: The MIT Press.

Lewins, J., and M. Becker, eds. 1982. "Sensitivity and Uncertainty Analysis of Reactor Performance Parameters." *Advances in Nuclear Science and Technology* 14, New York, NY: Plenum Press.

Liepmann, D., and G. Stephanopoulos. 1985. "Development and Global Sensitivity Analysis of a Closed Ecosystem Model." *Ecological Modelling* 30: 13-47.

Logan, S. E., and M. C. Berbano. 1978. *Development and Application of a Risk Assessment Method for Radioactive WAste Management, Volume II: Implementation for Terminal Storage in Reference Repository and Other Applications.* EPA 520/6-78-005. Washington, DC: U.S. Environmental Protection Agency.

Longsine, D. E., E. J. Bonano, and C. P. Harlan. 1987. *User's Manual for the NEFTRAN Computer Code*. NUREG/CR-4766, SAND86-2405. Albuquerque, NM: Sandia National Laboratories.

McCormick, N. J. 1981. *Reliability and Risk Analysis - Methods and Nuclear Power Applications*. New York: Academic Press.

McGrath, E. J., et al. 1975. *Techniques for Efficient Monte Carlo Simulation*. ORNL-RSIC-38, vols. I-III. Oak Ridge, TN: Oak Ridge National Laboratory.

McKay, M. D., W. J. Conover, and R. J. Beckman. 1979. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output From a Computer Code." *Technometrics* vol. 21, no. 2: 239-245.

McRae, G. J., J. W. Tilden, and J. H. Seinfeld. 1981. "Global Sensitivity Analysis--A Computational Implementation of the Fourier Amplitude Sensitivity Test (FAST)." *Computers and Chemical Engineering* 5: 15-25.

Marietta, M. G., S. G. Bertram-Howery, D. R. Anderson, K. Brinster, R. Guzowski, H. Iuzzolino, and R. P. Rechard. 1989. *Performance Assessment Methodology Demonstration: Methodology Development for Purposes of Evaluating Compliance with EPA 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant.* SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

Maerker, R. E. 1988. *Comparison of Results Based on a Deterministic Versus a Statistical Sensitivity Analysis*. ORNL/TM-10773. Oak Ridge, TN: Oak Ridge National Laboratory.

Mazumdar, M., et al. 1975. *Review of the Methodology for Statistical Evaluation of Reactor Safety Analysis*. EPRI 309. Palo Alto, CA: Electric Power Research Institute.

Mazumdar, M., et al. 1976. *Methodology Development for Statistical Evaluation of Reactor Safety Analyses*. EPRI-NP-194. Palo Alto, CA: Electric Power Research Institute.

Mazumdar, M., J. A. Marshall, and S. C. Chay. 1978. "Propagation of Uncertainties in Problems of Structural Reliability." *Nuclear Engineering and Design* 50: 163-167.

Mead, R., and D. J. Pike. 1975. "A Review of Response Surface Methodology from a Biometric Viewpoint." *Biometrics* 31: 803-851.

Mercer, J. W. 1983. *Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Los Medanos Area, Southeastern New Mexico.* U.S. Geological Survey, Water-Resources Investigations Report 83-4016. Albuquerque, NM: U.S. Geological Survey.

Mercer, J. W. 1987. *Compilation of Hydrologic Data from Drilling the Salado and Castile Formations Near the WIPP Site, Southeastern New Mexico.* SAND86-0954. Albuquerque, NM: Sandia National Laboratories.

Mercer, J. W., and B. R. Orr. 1977. *Review and Analysis of Hydrogeologic Conditions Near the Site of a Potential Nuclear-Waste Repository, Eddy and Lea Counties, New Mexico.* U.S. Geological Survey Open-File Report 77-123.

Mercer, J. W. and B. R. Orr. 1979. *Interim Data Report on Geohydrology of the Proposed Waste Isolation Pilot Plant, Southeast New Mexico.* U.S. Geological Survey Water Resources Investigation 79-98.

Mercer, J. W., R. L. Beauheim, R. P. Snyder, and G. M. Fairer. 1987. *Basic Data Report for Drilling and Hydrologic Testing of Drillhole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-0611. Albuquerque, NM: Sandia National Laboratories.

Milankovitch, M. M. 1941. *Canon of Insolation and the Ice-age Problem.* Koniglich Serbische Akademie, Beograd. (English translation by the Israel Program for Scientific Translations; published by the U.S. Department of Commerce and the National Science Foundation, Washington, D.C.).

Mishra, S., and J. C. Parker. 1989. "Effects of Parameter Uncertainty on Predictions of Unsaturated Flow." *Journal of Hydrology* **108**: 19-33.

Mitchell, J. F. B. 1989. "The 'Greenhouse Effect' and Climate Change." *Reviews of Geophysics* **27**: 115-139.

Molecke, M. A. 1983. *A Comparison of Brines Relevant to Nuclear Waste Experimentation.* SAND83-0516. Albuquerque, NM: Sandia National Laboratories.

Montgomery, R. H., V. D. Lee, and K. H. Reckhow. 1983. "Predicting Variability in a Lake Ontario Phosphorus Model." *Journal of Great Lakes Research* **9**: 74-82.

Morton, R. H. 1983. "Response Surface Methodology." *Mathematical Scientist* **8**: 31-52.

Muffler, L. J. P., ed. 1979. *Assessment of Geothermal Resources of the United States -- 1978.* Circular 790. U.S. Geological Survey.

Munson, D. E., Fossum, A. F., and Senseny, P. E. 1989a. *Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures.* SAND88-2948. Albuquerque, NM: Sandia National Laboratories.

Munson, D. E., Fossum, A. F., and Senseny, P. E. 1989b. *Approach to First Principles Model Prediction of Measured WIPP In Situ Room Closure in Salt.* SAND88-2535. Albuquerque, NM: Sandia National Laboratories.

Myers, R. H. 1971. *Response Surface Methodology.* Boston, MA: Allyn and Bacon.

Neter, J., and W. Wasserman. 1974. *Applied Linear Statistical Models.* Homewood, IL: Richard D. Irwin.

NEA (Nuclear Energy Agency). 1987. *Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems*. Paris: Organization for Economic Co-Operation and Development.

Nicholson, A., Jr., and A. Clebsch, Jr. 1961. *Geology and Ground-water Conditions in Southern Lea County, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Ground-Water Report No. 6. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Nowak, E. J., and J. C. Stormont. 1987. *Scoping Model Calculations of the Reconsolidation of Crushed Salt in WIPP Shafts*. SAND87-0879. Albuquerque, NM: Sandia National Laboratories.

Nowak, E. J., D. F. McTigue, and R. Beraun. 1988. *Brine Inflow to WIPP Disposal Rooms: Data, Modeling, and Assessment*. SAND88-0112. Albuquerque, NM: Sandia National Laboratories.

Nowak, E. J., J. R. Tillerson, and T. M. Torres. 1990. *Initial Reference Seal System Design: Waste Isolation Pilot Plan*. SAND90-0355. Albuquerque, NM: Sandia National Laboratories.

NuPac (Nuclear Packaging, Inc.). 1989. *Safety Analysis Report for the TRUPACT-II Shipping Package*. NuPac TRUPACT-II SAR Rev. 4.

Oblow, E. M. 1985. *GRESS: Gradient Enhanced Software System, Version D, User's Guide*. ORNL/TM-9658. Oak Ridge, TN: National Laboratory.

Oblow, E. M., F. G. Pin, and R. Q. Wright. 1986. "Sensitivity Analysis Using Computer Calculus: A Nuclear Waste Isolation Example." *Nuclear Science and Engineering* **94**: 46-65.

Obray, C. D, C. C. Wright, and S. J. Baldwin. 1986. "A Comparative Study of Monte-Carlo Simulation and Taylor Series Approaches to the Derivation of Uncertainty Estimates: A Case Study on Compact Heat Exchangers" in *Modelling Under Uncertainty 1986*. Eds. S. B. Jones and D. G. S. Davies. Institute of Physics Conference Series No. 80: 243-252. Bristol, England: Institute of Physics.

Olivi, L. 1986. *Response Surface Methodology Handbook for Nuclear Reactor Safety*. EUR 9600 EN. Luxembourg: Commission of the European Communities.

Ortiz, N. R., T. A. Wheeler, R. J. Breeding, S. Hora, M. A. Myer, and R. L. Keeney. 1991. "Use of Expert Judgment in NUREG-1150." *Nuclear Engineering and Design*. **126**: 313-331.

Owen, G. N., and R. E. Scholl. 1981. *Earthquake Engineering of Large Underground Structures*. FHWA/RD-80/195. Washington, D.C.: Federal Highway Administration, Department of Transportation.

Parker, T. J., and A. N. McDowell. 1951. "Scale Models as Guides to Interpretation of Salt Dome Faulting." *American Association of Petroleum Geologists Bulletin* vol. 35, no. 9: 2076-2086.

Parker, T. J., and A. N. McDowell. 1955. "Model Studies of Salt dome Tectonics." *American Association of Petroleum Geologists Bulletin* vol. 39, no. 12: 2384-2470.

Parry G. W. 1988. "On the Meaning of Probability in Probabilistic Safety Assessment." *Reliability Engineering and System Safety* **23**: 309-314.

Pasztor, S. B. 1991. "A Historical Perspective of Cultural Development in Southeastern New Mexico," Chapter IX in *Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*. Eds. R. V. Guzowski and M. M. Gruebel. SAND91-0928. Albuquerque, NM: Sandia National Laboratories. In preparation.

Paté-Cornell M. E. 1986. "Probability and Uncertainty in Nuclear Safety Decisions." *Nuclear Engineering and Design* **93**: 319-327.

Pepping, R. E., M. S. Y. Chu, and M. D. Siegel. 1983. "A simplified analysis of a hypothetical repository in a basalt formation, Volume 2." *Technical Assistance for Regulatory Development: Review and Evaluation of the Draft EPA Standard 40 CFR 191 for Disposal of High-Level Waste*. NUREG/CR-3235, SAND82-1557. Albuquerque, NM: Sandia National Laboratories.

Peterson, E. W., P. L. Lagus, and K. Lie. 1987. *Fluid Flow Measurements of Test Series A and B for the Small Scale Seal Performance Tests*. SAND87-7041. Albuquerque, NM: Sandia National Laboratories.

Pin, F. G., B. A. Worley, E. M. Oblow, R. Q. Wright, and W. V. Harper. 1986. "An Automated Sensitivity Analysis Procedure for the Performance Assessment of Nuclear Waste Isolation Systems." *Nuclear and Chemical Waste Management* **6**: 255-263.

Popielak, R. S., R. L. Beauheim, S. R. Black, W. E. Coons, C. T. Ellingson, and R. L. Olson. 1983. *Brine Reservoirs in the Castile Fm., Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. TME-3153. Carlsbad, NM: U.S. Department of Energy.

Powers, D. W., S. J. Lambert, S-E Shaffer, L. R. Hill, and W. D. Weart, eds. 1978a. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. Volume I*. SAND78-1596. Albuquerque, NM: Sandia National Laboratories.

Powers, D. W., S. J. Lambert, S-E Shaffer, L. R. Hill, and W. D. Weart, eds. 1978b. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. Volume II*. SAND78-1596. Albuquerque, NM: Sandia National Laboratories.

Public Law 96-164. 1979. *Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980*.

Public Law 100-456. 1989. *National Defense Authorization Act, Fiscal Year 1989*.

Rabitz, H., M. Kramer, and D. Dacol. 1983. "Sensitivity Analysis in Chemical Kinetics." *Annual Reviews of Physical Chemistry* **34**: 410-461.

Rackwitz, R., and B. Fiessler. 1978. "Structural Reliability Under Combined Random Load Sequences." *Journal of Computers and Structures* **9**: 489-494.

Rautman, C. 1988. *Technical Data Base Planning Strategy for the NNWSI Site & Engineering Properties Data Base*. SLTR87-5003. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P. 1989. *Review and Discussion of Code Linkage and Data Flow in Nuclear Waste Compliance Assessments*. SAND87-2833. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., H. J. Iuzzolino, J. S. Rath, R. D. McCurley, and D. K. Rudeen. 1989. *User's Manual for CAMCON: Compliance Assessment Methodology Controller*. SAND88-1496. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., H. J. Iuzzolino, and J. S. Sandha. 1990a. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*. SAND89-2408. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., W. Beyeler, R. D., McCurley, D. K. Rudeen, J. E. Bean, and J. D. Schreiber. 1990b. *Parameter Sensitivity Studies of Selected Components of the WIPP Repository System*. SAND89-2030. Albuquerque, NM: Sandia National Laboratories.

Reiter, L. 1990. *Earthquake Hazard Analysis*. New York, NY: Columbia University Press.

Richey, S. F., J. G. Wells, and K. T. Stephens. 1985. *Geohydrology of the Delaware Basin and Vicinity, Texas and Mexico*. U.S. Geological Survey Water Resources Investigations Report 84-4077. Washington, DC: U.S. Geological Survey.

Rish, W. R., and R. J. Marnicio. 1988. *Review of Studies Related to Uncertainty in Risk Analysis*. ORNL/TM-10776. Oak Ridge, TN: Oak Ridge National Laboratory.

Robinson, T. W., and W. B. Lang. 1938. *Geology and Groundwater Conditions of the Pecos River Valley in the Vicinity of Laguna Grande de la Sal, New Mexico, With Special Reference to the Salt Content of the River Water*. New Mexico State Engineer 12th-13th Biennial Rpts 1934-1938. 77-100.

Ronen, Y, ed. 1988. *Uncertainty Analysis*. Boca Raton, FL: CRC Press.

Rose, K. A.. 1982. "A Simulation Comparison and Evaluation of Parameter Sensitivity Methods Applicable to Large Models" in *Analysis of Ecological Systems: State-of-the-Art in Ecological Modeling*. Eds. W. K. Lauenroth, et al. 129-140.

Rose, K. A., and G. S. Swartzman. 1981. *A Review of Parameter Sensitivity Methods Applicable to Ecosystem Models*. NUREG/CR-2016. Seattle, WA: University of Washington.

Sanford, A. R., and T. R. Toppozada. 1974. *Seismicity of Proposed Radioactive Waste Disposal Site in Southeastern New Mexico*. Circular 143. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Saulnier, G.J. Jr. 1987. *Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-11 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*. SAND87-7124. Albuquerque, NM: Sandia National Laboratories.

Saulnier, G. J., Jr., and J. D. Avis. 1988. Interpretation of Hydraulic Tests Conducted in the Waste-Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site. SAND87-7001. Albuquerque, NM: Sandia National Laboratories.

Scavia, D., W. F. Powers, R. P. Canale, and J. L. Moody. 1981. "Comparison of First-Order Error Analysis and Monte Carlo Simulation in Time-Dependent Lake Eutrophication Models." *Water Resources Research* **17**: 1051-1059.

Schaibly, J. H., and K. E. Shuler. 1973. "Study of the Sensitivity of Coupled Reaction Systems to Uncertainties in Rate Coefficients, II. Applications." *Journal of Chemical Physics* **59**: 3879-3888.

Schwarz, G., and F. O. Hoffman. 1980. "Imprecision of Dose Predictions for Radionuclides Released to the Environment: An Application of a Monte Carlo Simulation Technique." *Environment International* **4**: 289-297.

Seaholm, S. K., E. Ackerman, and S. C. Wu. 1988. "Latin Hypercube Sampling and the Sensitivity Analysis of a Monte Carlo Epidemic Model." *International Journal of BioMedical Computing* **23**: 97-112.

Shurbet, D. H. 1969. "Increased Seismicity in Texas." *Texas Journal of Science* **21**: 37-41.

Siegel, M. D. 1990. "Appendix A, Memo 3a: Representation of Radionuclide Retardation in the Culebra Dolomite in Performance Assessment Calculations," in *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)*. R. P. Rechard, H. Iuzzolino, and J. S. Sandha. SAND89-2408. Albuquerque, NM: Sandia National Laboratories.

Siegel, M. D., and S. J. Lambert. 1991. "Summary of Hydrogeochemical Constraints on Groundwater Flow and Evolution in the Rustler Formation," Chapter I in *Hydrogeochemical Studies of the Rustler Formation and Related*

Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico. Eds. M. D. Siegel, S. J. Lambert, and K. L. Robinson. SAND88-0196. Albuquerque, NM: Sandia National Laboratories.

Siegel, M. D., K. L. Robinson, and J. Myers. 1991. "Solute Relationships in Groundwaters from the Culebra Dolomite and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico," Chapter 2 in *Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico.* SAND88-0196. Albuquerque, NM: Sandia National Laboratories.

Slezak, S., and A. Lappin. 1990. "Potential for and Possible Impacts of Generation of Flammable and/or Detonable Gas Mixtures during the WIPP Transportation, Test, and Operational Phases," memorandum to D. Mercer and C. Fredrickson (January 5). Albuquerque, NM: Sandia National Laboratories.

Smith, C. B., D. J. Egan, Jr., W. A. Williams, J. M. Grunlke, C.-Y. Hung, and B. L. Serini. 1982. *Population Risks from Disposal of High-Level Radioactive Wastes in Geologic Repositories.* EPA-520/3-80-006. Washington, D.C.: U.S. Environmental Protection Agency.

Snyder, R. P. 1985. "Dissolution of Halite and Gypsum, and Hydration of Anydrite to Gypsum, Rustler Formation, in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico," Open-File Report 85-229. Denver, CO: U.S. Geological Survey.

Snyder, R. P., and L. M. Gard. 1982. *Evaluation of Breccia Pipes in Southeastern New Mexico and their Relation to the Waste Isolation Pilot Plant (WIPP) Site.* Open-File Report 82-968. Washington, D.C.: U.S. Geological Survey for the U.S. Department of Energy (Interagency Agreement E (29-2)-3627).

Stormont, J. C. 1988. *Preliminary Seal Design Evaluation for the Waste Isolation Pilot Plant.* SAND87-3083. Albuquerque, NM: Sandia National Laboratories.

Stormont, J. C., E. W. Peterson, and P. L. Lagus. 1987. *Summary of and Observations about WIPP Facility Horizon Flow Measurements through 1986.* SAND87-0176. Albuquerque, NM: Sandia National Laboratories.

Stratton, W. R. 1983. *The Myth of Nuclear Explosions at Waste Disposal Sites.* LA-9360. Los Alamos, NM: Los Alamos National Laboratory.

Sykes, J. F., and N. R. Thomson. 1988. "Parameter Identification and Uncertainty Analysis for Variably Saturated Flow." *Advances in Water Resources* 11: 185-191.

Swift, P. N. 1991a. "Long-Term Climate Variability at the Waste Isolation Pilot Plant," Chapter VII in *Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant.* Eds. R. V. Guzowski and M. M. Gruebel. SAND91-0928. Albuquerque, NM: Sandia National Laboratories. In preparation.

Swift, P. N. 1991b. "Agriculture and Climatic Change at the Waste Isolation Pilot Plant," Chapter VIII in *Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant.* Eds. R. V. Guzowski and M. M. Gruebel. SAND91-0928. Albuquerque, NM: Sandia National Laboratories. In preparation.

Taylor, L. M., D. P. Flanagan, and W. C. Mills-Curran. 1987. *The GENESIS Finite Element Mesh File Format.* SAND86-0910. Albuquerque, NM: Sandia National Laboratories.

Thorne, B. J., and D. K. Rudeen. 1979. *Regional Effects of TRU Repository Heat.* CSI-2053-05. Albuquerque, NM: Civil Systems, Inc.

Tierney, M. S. 1990. *Constructing Probability Distributions of Uncertain Variables in Models of the Performance of the Waste Isolation Pilot Plant.* SAND90-2510. Albuquerque, NM: Sandia National Laboratories.

Tilden, J. W., V. Costanza, G. J. McRae, and J. H. Seinfeld. 1981. "Sensitivity Analysis of Chemically Reacting Systems" in *Modelling of Chemical Reaction Systems.* Eds. K. H. Ebert, P. Deuflhard and W. Jaeger (eds). New York, NY: Springer-Verlag. 69-91.

Tomovic, R., and M. Vukobratovic. 1972. *General Sensitivity Theory.* New York, NY: Elsevier.

Trauth, K. M., R. P. Rechard, and S. C. Hora. 1991. "Expert Judgment as Input to Waste Isolation Pilot Plant Performance Assessment Calculations: Probability Distributions of Significant System Parameters" in *Mixed Waste: Proceedings of the First International Symposium, August 26-29, Baltimore, Maryland.* Eds. A. A. Moghissi and G. A. Benda. American Society of Mechanical Engineers, U.S. Department of Energy, U.S. Environmental Protection Agency, and the University of Maryland

Trusheim, F. 1960. "On the Mechanism of Salt Migration in Northern Germany." *American Association of Petroleum Geologists Bulletin* vol. 44, no. 9: 1519-1540.

Tyler, L. D., R. V. Matalucci, M. A. Molecke, D. E. Munson, E. J. Nowak, and J. C. Stormont. 1988. *Summary Report for the WIPP Technology Development Program for Isolation of Radioactive Waste.* SAND88-0844. Albuquerque, NM: Sandia National Laboratories.

U.S. DOE (Department of Energy). 1979. *Draft Environmental Impact Statement, Management of Commercially Generated Radioactive Waste.* DOE/EIS-0046-D. Washington, DC: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1980a. *Final Environmental Impact Statement: Waste Isolation Pilot Plant.* DOE/EIS-0026. U.S. Department of Energy, October 1980.

U.S. DOE (Department of Energy). 1980b. *Subject: Radioactive Waste Management.* DOE Order 5820.2A, dated September 26, 1988.

U.S. DOE (Department of Energy). 1981. "Waste Isolation Pilot Plant (WIPP); Record of Decision." *Federal Register* **46**: 9162.

U.S. DOE (Department of Energy). 1987. *A Plan for the Implementation of Assurance Requirements in Compliance with 40 CFR Part 191.14 at the Waste Isolation Pilot Plant*. DOE/WIPP 87-016. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1988. *Geotechnical Field Data and Analysis Report*. DOE-WIPP-87-017. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1989a. *Waste Isolation Pilot Plant Compliance Strategy for 40 CFR Part 191*. WIPP-DOE-86-013. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1989b. *Draft Supplement Environmental Impact Statement, Waste Isolation Pilot Plant*. DOE/EIS-0026-DS. Washington, DC: U.S. Department of Energy, Office of Enviromental Restoration and Waste Mmanagement.

U.S. DOE (Department of Energy). 1989c. *Annual Water Quality Data Report, Waste Isolation Pilot Plant*, DOE/WIPP 89-001. Carlsbad, NM: Westinghouse Electric Corporation.

U.S. DOE (Department of Energy). 1990a. *Final WIPP Safety Analysis Report, Waste Isolation Pilot Plant*. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1990b. *WIPP Test Phase Plan: Performance Assessment*. DOE/WIPP 89-011, Rev. 0. Carlsbad, NM.

U.S. DOE (Department of Energy). 1990c. *Final Supplement Environmental Impact Statement, Waste Isolation Pilot Plant*. DOE/EIS-0026-FS. Washington, DC: U.S. Department of Energy, Office of Environmental Restoration and Waste Management.

U.S. DOE (Department of Energy). 1990d. *Recommended Initial Waste Forms for the WIPP Experimental Test Program, May 1990, Engineered Alternnatives Task Force*. DOE/WIPP 90-009. Carlsbad, NM: Westinghouse Electric Corporation.

U.S. DOE (Department of Energy). 1990e. *Integrated Data Base for 1990: Spent Fuel and Radioactive Waste Inventories, Projects and Characterizations*. DOE/RW-006, Rev. 6.

U.S. DOE (Department of Energy). 1990f. *Waste Isolation Pilot Plant No-Migration Variance Petition*. DOE/WIPP 89-003, Revision 1. Carlsbad, NM: Westinghouse Electric Corporation.

U.S. DOE (Department of Energy). 1991a. *Strategy for the Waste Isolation Pilot Plant Test Phase*. DOE/EM/48063-2. Washington, DC: Office of Waste Operations, U.S. Department of Energy.

U.S. DOE (Department of Energy). 1991b. *Waste Isolation Pilot Plant Test Phase Management Plan*. DOE/WIPP91-015. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1991c. *Recommended Strategy for the Remote-Handled Transuranic Waste Program*. DOE/WIPP 90-058, Revision 1. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1991d. *Implementation of the Resource Disincentive in 40 CFR Part 191.14(e) at the Waste Isolation Pilot Plant* DOE/WIPP 91-029. Carlsbad, NM: U.S. Department of Energyy.

U.S. DOE (Department of Energy) and State of New Mexico. 1981, as modified. "Agreement for Consultation and Cooperation" on WIPP by the State of New Mexico and U.S. Department of Energy, modified 11/30/84 and 8/4/87.

U.S. EPA (Environmental Protection Agency). 1984. *Ground-Water Protection Strategy*. Washington, DC: Office of Ground-Water Protection.

U.S. EPA (Environmental Protection Agency). 1985. *Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste; Final Rule*, 40 CFR Part 191, *Federal Register* **50**: 38066-38089.

U.S. NRC (Nuclear Regulatory Commission). 1975. *Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants:* U.S. Nuclear Regulatory Commission Rept. WASH-1400, NUREG-75/014. Washington, DC.

U.S. NRC (Nuclear Regulatory Commission). 1990. *Severe Accident Risks: An Assessment forr Five U.S. Nuclear Power Plants*. NUREG-1150. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Uliasz, M. 1985. "Comparison of the Sensitivity Analysis Methods for Meteorological Models." *Zeitschrift fuer Meteorologie* **6**: 340-348.

University of New Mexico. 1989. *New Mexico Statistical Abstract 1989*. Albuquerque, NM: Bureau of Business and Economic Research, University of New Mexico.

Vaughn, P., J. Schreiber and J. Bean. 1991. "The Modeling and Effect of Waste-Generated Gas of Probabilistic System Assessments of the Waste Isolation Pilot Plant" in *Proceedings of NEA Workshop on Gas Generation and Release from Radioactive Waste Repositories, Aix-en-Provence, France. September 23-26, 1991*. In preparation.

Vaughn, W. A. 1982. "Review of the Environmental Analysis for the Cost Reduction Proposals for the Waste Isolation Pilot Plant (WIPP) Project," letter to H. E. Roser, Assistant Secretary for Defense Programs (July 8). Washington, D.C.: Environmental Protection, U.S. Department of Energy.

Vesely, W. E. and D. M. Rasmuson. 1984. "Uncertainties in Nuclear Probabilistic Risk Analyses." *Risk Analysis* 4: 313-322.

Vine, J. D. 1963. "Surface Geology of the Nash Draw Quadrangle, Eddy County, New Mexico." *U.S. Geological Survey Bulletin* 1141-B.

Voss, C. I. 1984. *SUTRA (Saturated-Unsaturated Transport): A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Density-Dependent Ground-Water Flow with Energy Transport or Chemically Reactive Single-Species Solute Transport*. Reston, VA. U.S. Geological Survey National Center.

Ward, R. F., C. G. St. C. Kendall, and P. M. Harris. 1986. "Upper Permian (Guadalupian) Facies and Their Association with Hydrocarbons - Permian Basin, West Texas and New Mexico." *American Association of Petroleum Geologists Bulletin* 70: 239-262.

Waste Management Technology Department. 1987. *The Scientific Program at the Waste Isolation Pilot Plant*. SAND85-1699. Albuquerque, NM: Sandia National Laboratories.

Weart, W. D. 1983. *Summary of Evaluation of the Waste Isolation Pilot Plant (WIPP) Site Suitability*. SAND83-0450. Albuquerque, NM: Sandia National Laboratories.

Weatherby, J. R., J. G. Arguello, and C. M. Stone. 1989. "The Effect of Gas Generation on Performance of CH-TRU Disposal Rooms," memorandum to B. M. Butcher (November 14). Albuquerque, NM: Sandia National Laboratories.

Weatherford, R. 1982. *Philosophical Foundations of Probability Theory*. London, UK: Routledge and Kegan Paul, Ltd.

WEC (Westinghouse Electric Corporation). 1989. *Waste Isolation Pilot Plant Underground Facility Plan*. Drawing No. 51-W-032-W, revision C, sheet 1 of 1. Carlsbad, NM: Westinghouse Waste Isolation Division.

WEC (Westinghouse Electric Corporation). 1990. *Final Program Plan for Engineered Alternatives*. April 20, 1990, Carlsbad, New Mexico.

Wheeler, T. A., S. C. Hora, W. R. Cramond, and S. D. Unwin. 1989. *Analysis of Core Damage Frequency: Expert Judgment Elicitation*. NUREG/CR-4550, SAND86-1084, vol. 2, rev. 2. Albuquerque, NM: Sandia National Laboratories.

Williamson, C. R. 1978. "Depositional Processes, Diagenesis and Reservoir Properties of Permian Deep-Sea Sandstone, Bell Canyon Formation." Ph.D. dissertation. University of Texas, Austin, TX.

Winkler, R. L. 1972. *An Introduction to Bayesian Inference and Decision*. New York: Holt, Reinhart and Winston.

Woo, G. 1991. "A Quitting Rule for Monte Carlo Simulation of Extreme Risks." *Reliability Engineering and System Safety* 31: 179-189.

Worley, B. A., and J. E. Horwedel. 1986. *A Waste Package Performance Assessment Code with Automated Sensitivity-Calculation Capability.* ORNL/TM-9976. Oak Ridge, TN: Oak Ridge National Laboratory.

Wu, Y.-T. 1987. "Demonstration of a New, Fast Probability Integration Method for Reliability Analysis." *Journal of Engineering for Industry* **109**: 24-28.

Wu, Y.-T., and P. H. Wirsching. 1987. "New Algorithm for Structural Reliability." *Journal of Engineering for Industry* **113**: 1319-1336.

Wu, Y.-T., H. R. Millwater, and T. A. Cruse. 1990. "Advanced Probabilistic Structural Method for Implicit Performance Functions." *AIAA Journal* **28**: 1663-1669.

Wu, Y. -T., A. G. Journel, L. R. Abramson, and P. K. Nair. 1991. *Uncertainty Evaluation Methods for Waste Package Performance Assessment.* NUREG/CR-5639. Washington, DC: Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission.

Zimmerman, D. A., K. K. Wahi, A. L. Gutjahr, and P. A. Davis. 1990. *A Review of Techniques for Propagating Data and Parameter Uncertainties in High-Level Radioactive Waste Repository Performance Models.* NUREG/CR-5393, SAND89-1432. Albuquerque, NM: Sandia National Laboratories.

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

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:
RESPONSE TO REVIEW COMMENTS

APPENDIX B: RESPONSE TO REVIEW COMMENTS

Comments in this appendix relate to SAND90-2347, *Preliminary Comparison with CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990.* Responses relate to SAND91-0893, the 1991 version of SAND90-2347.

Response to Comments from New Mexico Environment Department

COMMENT 1. Page I-6, first paragraph: 2000 m equals 6560 feet.

RESPONSE: Metrication error has been corrected.

COMMENT 2. Page I-30, sixth paragraph: How important is it that the Rustler formation includes hydrostratigraphic units that provide potential pathways for radionuclide migration away from the WIPP, with so much halite of the Salado formation to cross?

RESPONSE: The Culebra Dolomite in the Rustler Formation is the primary water-producing unit between the waste panels and the surface. Although the thickness of the bedded salt between the panels and the Culebra would be expected to act as a barrier to radionuclides migrating to the Rustler, the shafts and exploratory boreholes will provide possible pathways through the salt for waste in the panels to reach the overlying units. Because of these possible pathways through the salt, possible transportation pathways within the Rustler Formation must be considered.

COMMENT 3. Page III-34: What is the meaning of CCDFs crossing the Containment Requirement?

RESPONSE: A CCDF that extends to the right of the line labeled "Containment Requirement" (see Figure 3-9 in Volume 1 of SAND91-0893) indicates that for one (or more) scenarios S_i analyzed the pair (S) ($pS_i(\mathbf{x}_k)$, $cS_i(\mathbf{x}_k)$) lies beyond the EPA limits of (0.1, 1.0) and (0.001, 10.0) for the specific sample element, $\mathbf{x}_k$.

Since the parameter values in the sample element, $\mathbf{x}_k$, are not known to be correct with certainty, the full family of CCDFs must be considered. Mean and percentile curves, e.g., median, (see Figure 3-10, Volume 1 of SAND91-0893) are suitable summary curves for comparison to the requirement.

For example, if the 90% quantile curve lies to the left of the Containment Requirement, then compliance is indicated with at least a 90% level-of-confidence conditional on the assumed conceptual and mathematical models, the assigned ranges and distributions for uncertain parameters, the scenarios, and all other assumptions used in the analyses, as discussed in Chapter 6, Volume 1 of SAND91-0893.

COMMENT 4. Page V-18, last paragraph: What method was used to convert darcies into m/s? A darcy is a unit of permeability (m^2) while m/s is a unit of conductivity.

RESPONSE: The conversion was based on Table 2.3 (Conversion Factors for Permeability and Hydraulic Conductivity Units) in *Groundwater* by R. A. Freeze and J. A. Cherry (1979).

COMMENT 5. Page V-74, second paragraph: The decay product of Radium-226 is Radon-222 (not 226) with a half-life of 3.825 days.

RESPONSE: The correction has been made.

COMMENT 6. Page VI-6, Table VI-1: Bulk Shear Stress 1 to 5 Pa?? MPa maybe.

RESPONSE: As more carefully explained in Volume 3, Section 3.4 of SAND91-0893, this effective shear stress of the waste equals the fluid stress at which sediment movement (erosion) from a bed of clay particles is general. It is smaller by several orders of magnitude from the macroscopic soil shear strength, and in the absence of real data for waste materials, is used as a conservative estimate.

COMMENT 7. Page VI-17: Abscissa should read: 10^{-15} m^2 and 10^{-13} m^2.

RESPONSE: The errors in the figure have been noted. This figure is not repeated in SAND91-0893.

COMMENT 8. Page VI-18: Time should read Time*10^3 years.

RESPONSE: The errors in the figure have been noted. This figure is not repeated in SAND91-0893.

COMMENT 9. Page VI-27: Distance should read Distance*10^3 m?

RESPONSE: The labeling errors in Figures VI-11 and VI-12 have been noted. These figures are not repeated in SAND91-0893.

Response to Comments from the Environmental Evaluation Group

COMMENT 1. Abstract (i - ii): The abstract clearly elucidates areas of uncertainty in performance assessment of the WIPP for compliance with 40 CFR Part 191, Subpart B:

a. sensitivity analysis and parameter distribution determinations;

b. construction of mean CCDF curves for scenarios included within the analysis from families of curves resulting from Latin Hypercube sampling of parameter distributions;

c. a significant increase in retardation factors due to clay-lined fractures and assumption of a dual-porosity model;

d. the effects of gas generation in the repository on brine flow and radionuclide transport and the preliminary nature of their use in performance assessment.

However, an equally important area of uncertainty not mentioned in the abstract is scenario probability assignments which have considerable influence on CCDF formulation, not only because there are significant differences in assignments between investigators, but also because they have been utilized deterministically in this PA analyses, and have significant impact on the ordinate of the CCDF curves. Also, there appears to have been a significant reduction of radionuclide release to the ground surface from human intrusion boreholes, notwithstanding scenario probability assignments, and this topic should merit attention in the abstract.

RESPONSE: These points should have been summarized in the abstract for SAND90-2347. The abstracts for the volumes of SAND91-0893 will be overviews of significant information contained in the volumes.

COMMENT 2. Page ES-3, Lines 10-13: It is stated that the "mean" CCDF's produced by this analysis are within the EPA limits. It would be equally important to note how many of the Latin Hypercube Samples (LHS) utilized in these analyses exceeded the EPA limits, and/or an exceedance frequency reported. A reported mean CCDF without a variance estimate does not convey this equally important type of information.

RESPONSE: This point was illustrated in examples of families of CCDFs in Chapter III of SAND90-2347. The subject is discussed in Volume 1, Chapter 3 of SAND91-0893 and is also illustrated in the figures in Chapter 6 of Volume 1.

COMMENT 3. Page ES-4, Lines 18-24: Whereas it is understandable that climatic change (TC) has not been incorporated into the model as part of the base case scenario at this time, the reason for exclusion of subsidence to the surface (TS) associated with potash mining is not clearly stated. Subsidence was assigned a probability of 0.05 ([Marietta et al., 1989] SAND89-2027, p. IV-46) based on the fact that it has been observed in the Delaware Basin, although it was not utilized in the methodological demonstration. It would appear that the main reason for excluding it from scenario development is that this type of event has yet to be incorporated into the modeling scheme because its effect on the Rustler Formation has not been fully conceptualized.

RESPONSE: Consequences of subsidence associated with potash mining have not been included in either the 1990 or 1991 preliminary performance assessments because, as the comment notes, "its effect on the Rustler Formation has not been fully conceptualized." Subsidence has not been excluded from scenario development, and its effects will be included in future consequence modeling.

A preliminary estimate of the effects of climatic change is included in the 1991 calculations, and will be refined and developed further in future analyses. The approach used to model the effects of subsidence may be analogous to that used in 1991 to approximate effects of climatic change.

COMMENT 4. Page I-6, Line 6: Conversion error ... about 2000 m (1,250 ft) ...

RESPONSE: Metrication error has been corrected.

COMMENT 5. Page I-38, Lines 39-40: Why was the 1987 IDB [U.S. DOE, 1987] used instead of the 1990 IDB (October 1990) [U.S. DOE, 1990a] for currently projected total radionuclide inventories by generator facility for CH and RH-TRU wastes?

RESPONSE: The CH radionuclide inventory was based on a draft of a Westinghouse report that used input to the 1987 IDB. This report had not been updated to include 1990 IDB input but was considered to be the best available CH radionuclide inventory. The RH radionuclide inventory was based on the 1990 IDB input as discussed in SAND89-2408, *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990)* (Rechard et al., 1990). The CH and RH radionuclide inventory in SAND89-2408, which differ somewhat from the values on Page I-38, Lines 13 to 26, were used in the analyses. The CH and RH radionuclide inventory for the 1991 analyses are based on input to the 1990 IDB.

COMMENT 6. Page II-3, Lines 22-26; Page II-11, Lines 1-4: The statement that inadvertent intrusion into the repository will lead to its detection goes beyond the guidance in the 1985 Standard and in Working Draft #3 which says "to soon detect, or be warned of, the incompatibility of the area with their activities." The thrust of their guidance seems to be that only inadvertent and intermittent intrusion need be considered, not persistent intrusion or exploitation of natural resources. Also, from a performance assessment (PA) point of view, the time interval before detection (and consequent borehole plugging) is important for some intrusion scenarios in ameliorating releases to the surface. In fact the E1 scenario depends on non-detection in the time interval it requires to reach the pressurized brine in the Castile Formation.

RESPONSE: The synopsis and text have been revised in Volume 1, Chapter 2 of SAND91-0893 to address this comment. The specific sentence in question, which was not consistent with the 1990 calculations, is not included in the 1991 report.

COMMENT 7. Page II-3, Lines 36-42; Page II-12, Lines 10-17: The statement about artificially reducing allowable releases by a factor of almost 3 suggests a misunderstanding of the EPA release limits. These rounded release limits relate to the radiological hazard of the radionuclide. Alpha-emitting transuranic elements have a higher hazard than shorter lived alpha-emitters or plutonium-241 (which is a beta emitter) and thus have a lower release limit. It is correct that some short-lived radionuclides decay to "regulated" daughter products but at a much lower curie level. For example a curie of Pu-241 will produce only 0.034 Ci of Americium-241 in its lifetime (and the maximum activity at any time would be 0.030 Ci). The inclusion of ingrowth Am-241 would increase the WIPP alpha-TRU inventory by only about 2.5%.

RESPONSE: The information in these paragraphs is no longer valid for the WIPP. Updated information is included in Volume 1, Chapter 1 of SAND91-0893.

COMMENT 8. Pages II-4 and 5, Lines 41, 45 and Lines 1-7; Page II-16, Lines 9-15: In light of the feeling that there is "reasonable confidence" that WIPP will meet the Standard, what is the purpose of this section for this report? Who is going to determine what "good isolation" means, and how will the restrictiveness of the requirements be evaluated, and by whom (EPA, DOE, ...)?

RESPONSE: This section was included to provide a complete overview of the Containment Requirements and is not intended to imply that the requirements will be modified. The EPA does not indicate who would make such determinations.

COMMENT 9. Page II-10, Lines 20-21: The statement that mining for resources need not be considered within the controlled area appears to be consistent with EPA guidance but it should be recognized that this may not be a conservative assumption for potash mining. In cases involving exploration for potash in the McNutt zone of the Salado Formation, no encounter with waste would occur and the prevention of exploitation would have to depend solely on passive institutional markers in the long term. This report references Hunter (SAND89-2546, 1989) which discusses a scenario involving solution mining of potash. This author states that Kaplan (ONWI-354, 1982) suggests that well designed markers supplemented by written records can be expected to last for 5,000 years and possibly 10,000 years. Kaplan, however, states that suitable stone markers such as exhibited by ancient monuments have survived in a variety of climates for up to 5,000 years (p. 49). In addition, the only reference to a 10,000 year marker survivability (except for the abstract) is with reference to marble and limestone markers (p. 43) which are not sufficiently durable for this period given the present levels of atmospheric pollution; and that markers constructed of modern metals such as titanium (p. 55) are not likely to survive this period of time because of recycling activities by Man. Also, this author states that about one-third to one-half of Stonehenge construction stone has been removed since it was built (p. 29). The phrase "very likely to survive 10,000 years" presented in the abstract of this report is nowhere substantiated in the report. Therefore, the exclusion of solution mining, and consequent subsidence scenario (TS) over the controlled area is seemingly not strongly supported by the Kaplan (1982) study for a 10,000 year period.

RESPONSE: The events and processes considered for scenario development have been rescreened in the 1991 report. Potash mining has been retained for further evaluation. Following the guidance in the Standard, future mining within the controlled area is excluded from consideration in performance assessment (PA) calculations. The possible effects of markers on future exploration have not been considered in the rescreening for the 1991 report. An expert panel on marker development will recommend design characteristics for "permanent" markers and judge efficacy of markers in deterring intrusion.

COMMENT 10. Page III-3, Lines 19-20; Page III-13, Lines 16-20: This statement is rather confusing because the probability of any event (for comparison with the EPA standard in this report) which constitutes part of a scenario is currently based on a binomial distribution:

$(p+q)^n$, where $q=(1-p)$, and $P(X)=(n!/X!(n-x)!)*p^X*q^{n-X}$, where $n=1$, $X=1$, and $P(X)=p$, and $q=1-p(X)$

and throughout this document, the event probabilities are held constant for PA comparisons, and both "yes" and "no" event occurrences (deterministic) are considered in the LHS sampling scheme. Hunter (SAND89-2546, 1989) describes the use of this distribution where n>1.0 for estimating the future number of borehole intrusions in the repository/rooms at WIPP over the long term. The term "probability distribution" refers to scenario LHS techniques developed for demonstration purposes, and the text should clarify that for PA in this report the term "probability" is appropriate. Furthermore, the "probability" of the probability distribution(s) utilized in this report for demonstration purposes should be documented if they are going to be used in future PA reports.

RESPONSE: The confusing text was poorly phrased and does not appear in SAND91-0893. A probability model has been developed for the 1991 performance assessment that includes stochastic variability rather than assuming fixed scenario (event) probabilities.

COMMENT 11. Page III-16, Line 16: The phrase "m input vectors," while understandable, appears awkward because "m" is undefined in the immediate vicinity of the phrase.

RESPONSE: This sentence does not appear in SAND91-0893.

COMMENT 12. Pages III-5 to III-7, Uncertainty analysis; Pages III-16 to III-37: Whereas this section is well written and understandable, there are a number of technical and philosophical concerns which create problems from both a statistical and data presentation viewpoint. Since the LHS technique permeates all aspects of uncertainty and sensitivity analysis for this PA, it is important to dwell on the advantages and disadvantages of this statistical tool because of its significant impact in the process of EPA compliance determination. As stated by Thomas (ONWI-380, 1982, p. 45): "The primary virtue of Latin Hypercube Sampling is the fact that it yields unbiased estimates of the probability density functions for computer outputs." Thomas also states that the LHS method is found to be inferior to conventional experimental designs for obtaining sensitivity coefficients for computer programs involving large numbers of equations and input parameters. The main problem with LHS utilization is in obtaining uncertainty information for individual input parameters in that it cannot control the type or extent of confounding among main effects and interactions in its operation. The problem is centered around the step-wise linear regression techniques that must be used to rank sensitivities of individual parameters which have covariances that vary with the specific magnitude of the parameters themselves. Thomas recommends an analytical approach, the adjoint method, as being superior for this purpose and it does not have the mentioned drawbacks of the LHS method in this endeavor. Although the parameter confounding issue has been mentioned in this report to be of concern, a more extensive discussion on the justification of LHS for this purpose in comparison to other methodologies such as the adjoint should be included in the PA report.

Another concern with this section is the manner of CCDF representation. Although EPA in the remanded Standard suggests the use of the mean or median CCDF (whichever is greatest) for the undisturbed or base case scenario in PA, it does not make such a suggestion for other types. Sandia National Laboratories (SNL) has interpreted this to mean that the "mean curve" is the primary measure in PA for the WIPP for both undisturbed and human intrusion scenarios. However, such representation does not convey any further information of the CCDF distribution function which the LHS procedure generated, and it would appear that anyone attempting to make a decision on "reasonable expectation" of compliance with the Standard would require variance information on the mean. In fact the graph showing all of the CCDF's for a given LHS sampling (Figure III-6) has more information from which to make a decision on this basis than has the mean CCDF for the same sampling (Figure III-7). Criteria other than the mean CCDF such as number of LHS samples generated, the fraction of CCDF's exceeding the Standard, the CCDF's bounding the samples, and percentile CCDF's are all equally important in making such decisions. The EPA guidance on this issue was certainly not intended to restrict supplying such information, and because EPA's intent is subject to interpretation, all relevant information should be presented when possible if it may have some bearing on the decision. Ancillary information of this type becomes particularly important when the mean CCDF is very close to EPA compliance limits (such as was the case in this report), or when the Standard is exceeded.

Also, there is some question as to the use of constant scenario probabilities for comparison to the Standard at this time without addressing the issue of the possible vertical displacements of the mean CCDF's when and if probability distributions (of events) are used to generate LHS scenarios from which such a mean is estimated. Since vertical displacements of the mean CCDF's may move such curves into the non-compliance portion of the Standard, it is important that the effect(s) be documented more fully in the report. Furthermore, it is not clear from reading this section that event probability distributions will ultimately be utilized in PA, and, therefore, the relevance of some of the examples presented (see Figure III-7) to this report has not been fully established.

RESPONSE: A detailed discussion on the reasons for using LHS techniques instead of other techniques such as the adjoint method is in Volume 1, Chapter 3 of SAND91-0893.

The full range of information generated from the performance assessment will be provided in the presentation of CCDFs for preliminary and final comparisons to the Standard.

COMMENT 13. Pages III-7 to III-8, Monte Carlo Techniques; Pages III-38 to III-42: The production of the mean CCDF in Figure III-14 from the family of CCDF's in Figure III-13 is unclear with respect to the ordinate.

The procedures for developing variable distributions for use in the WIPP PA are not given adequate attention in this report. Several of the secondary references are not currently available, and the available citation (Tierney 1990, SAND90-2510), and this report do not adequately discuss:

a. sufficient criteria used for selection of a specific distribution to be used in MEF formulation (SAND90-2510) other than identification of the source;

b. number of observations (or subjective estimates) used to construct the prior distributions using MEF;

c. justification that values used for any distribution are drawn from the same population (observations), and how many (if any) of these are subjective estimates (mixed models);

d. the relationship between the number of parameter observations (if any) used in a given distribution, the uncertainty in its use for LHS, and how the MEF conservatism impacts CCDF's in the PA;

e. why some other measures such as the mean, median, or the observations themselves (assumed not to be subjective) would not be more appropriate with or without LHS application;

f. limitations outlined in SAND90-2510 pertaining to effects of spatial averaging on variances used in lumped-parameter models, and the effects of possible correlations between parameters.

Whereas it is meaningless to question whether a subjectively selected prior distribution is an unbiased estimator of the actual parameter distribution when this decision is based on personal judgement, it is important to know how it will impact on the total uncertainty of a PA run where both statistically derived prior distributions, and those based on subjective criteria are concurrently utilized for LHS. In fact the resulting LHS operation confounds these effects, and both uncertainty and (to a certain extent) sensitivity analyses are similarly affected. What proportion of subjectively derived distributions are to be admitted, before one questions whether the resulting

PA can be considered to be based primarily on quantitative observations from the site, and not on subjective (Bayesian) judgement? This question is of particular importance when "sensitive" parameters are under consideration.

The use of MEF is a well known and established Bayesian reliability analysis technique used to produce prior distributions that may be termed conservative in nature depending on their application. This is accomplished by maximizing the Shannon equation (H): ... -(p1*ln(p1) + p2*ln(p2) + ... pn*(ln(pn)), where: p1, p2, . . . pn are probabilities of observing parameter estimates: x1, x2, ... xn from given parameter functions (ki, i=1, 2, ... m, m<n) (Martz et al., 1982, p. 231). The application of Shannon's equation is well established in biostatistical analysis in the determination of species diversity on gridded areas or volumes (cells): 1, 2, ... n. A maximum diversity is obtained when: p1 = p2 = ... pn, or the measure of diversity (H) is equal to ln(n). Unfortunately, the value is affected not only by the actual diversity itself, but also by the number of categories employed (n), and users frequently employ an "evenness" or "homogeneity" Shannon index (J) which is equal to (H/ln(n)). The latter expresses the observed diversity (H) as a proportion of the maximum value obtainable (ln(n)). The theoretical maximum diversity index is obtained when the observable parameter is equally distributed in all n cells. In general a well designed experiment to measure (H) will optimize the number and size of cells required, and insure randomization of cell selection to obtain a reliable estimate of the actual value (H*); and it can be expected that as the number of randomized observations increases, that the observed value (H) will become a better estimate of the actual (H*) based on statistical sampling theory.

Although not readily apparent in the available citation (SAND90-2510), the MEF should be subject to (H) and (J) type determinations, and to the optimization techniques applied to the biostatistical example just described for comparison. Where observed values for a given parameter are representative and in good supply, it would be expected that a better representation of the actual distribution of the parameter would be obtained than when a smaller number of observations are available. The "evenness" concept would be expected to produce distributions satisfying the method of maximum entropy, however, there is no discussion in this report of the robustness of this technique with respect to prior distribution selection where the number of observables are relatively sparse. There is also some confusion when parameter distributions derived from statistical sampling theory and Bayesian MEF derived distributions involving sparse or non-existent data are given equal weighting in the LHS process. Any uncertainty and sensitivity analysis is bound to involve subjective/objective interactions that may be difficult if not impossible to identify using this mixed methodology, and will impact on decisions regarding CCDF evaluations. The references cited do not appear to address this issue.

Finally, it is not readily apparent that because MEF produced parameter distributions are conservative by design, that their application utilizing LHS for mean CCDF production are also conservative. For example, the production of large retardation factors from LHS of an MEF prior distribution factor of this parameter presented in this report would be expected to shift a given CCDF toward the compliance part of the Standard while the minimum retardation factor (1) is held constant. In fact MEF distributions which conservatively estimate upper or lower values can be shown to shift the CCDF in a non-conservative direction. It would appear that sensitive parameters that exhibit this type of behavior should be given more extensive field study based on statistical sampling theory to give possibly less conservative, but more realistic, distribution functions for use in PA. This report has not adequately justified the effects of MEF on CCDF construction.

RESPONSE: Production of a mean (or median, or p-percentile) CCDF from a family of CCDFs is discussed in some detail in the sections "Characterizing Uncertainty in Risk," pages III-23 to III-29, and "Risk and the EPA Limits," pages III-29 to III-33 in SAND90-2347.

13a. Criteria and procedures for developing probability distributions of parameters from currently available information were explained in SAND90-2510 (Tierney, 1990).

13b. The number of observations (or subjective estimates) used to construct empirical (or subjective) distributions was usually not mentioned either in SAND90-2347, or in the companion data report (Rechard et al., 1990, SAND89-2408), and is not adequately discussed in 1991. However, a thorough discussion of data is a high priority in 1992.

13c. None of the distributions in SAND89-2408 (Rechard et al., 1990) arose from mixed models; most distributions were subjective and based on range and subjective estimates of median (50th percentile).

13d. The sensitivity of CCDFs to changes in the <u>forms</u> of parameter probability distributions was not investigated in the 1990 PA exercise or in SAND91-0893.

13e. In some cases, summary measures such as mean or median would have been more appropriate choices for parameters, but distributions were nevertheless used to test for sensitivity and incorporate a (perhaps unnecessary) conservation in the analyses. See Section 1.2 in Volume 3 of SAND91-0893 for further discussion.

13f. As stated, these limitations were clearly stated in SAND90-2510 (Tierney, 1990).

Sensitivity and uncertainty analyses are "blind" to the origin of the parameter distributions that are employed in those kinds of analyses. The main question is: How sensitive are the results of, say, an uncertainty analysis to changes in the forms of the underlying parameter distributions? As stated above [13d.], no such sensitivity studies were conducted in the 1990 PA exercise.

Most comments on maximum entropy formalism (MEF) concern fine points of using MEF in Bayesian reliability analysis. The best response to these comments is the following explanation of why MEF was used in the 1990 PA exercise. The MEF was invoked in the 1990 PA exercise (Tierney, 1990, SAND90-2510) for only two reasons: 1) MEF provides an accepted technique for constructing a prior distribution when only subjective estimates of the moments (e.g., mean and variance) of the distribution are provided by experts; and 2) MEF can be used to justify connecting the points of a step-like empirical cdf (whether based on measurements or on subjective estimates of percentiles) with straight lines instead of some other curve (e.g., splines or quadratics). In actual practice, during the data gathering for the 1990 exercise, no one submitted subjective estimates of mean/variance; the MEF proved useful only in the sense of reason 2.

COMMENT 14. Page III-48, Performance Assessment Process: The reference in Table III-1 lists an improvement for 2-D radionuclide transport with a retardation submodel involving dual-porosity clay-lined fractures and other specified conditions. However, no mention is made of the C&C agreement which requires the use of a retardation factor of one (1) barring tracer experiments to make firmer estimates of this parameter. A baseline simulation where no credit is taken for retardation should be included in this report to scope out the effect of this parameter on the PA if such experiments are not forthcoming. Also, it appears that Bayesian reliability methodology has been used to make the retardation distributions which contain subjective judgement about this parameter for a specific radionuclide, and is not based purely on statistical sampling theory. How does this impact on the C & C agreement? Finally, a sensitivity analysis of retardation factors generated for use in the PA is not reported in this document.

RESPONSE: Uncertainty/sensitivity analyses of 1991 results, including parameters for chemical and physical retardation, are in Volume 4 of SAND91-0893. Construction of cdf's for these parameters is included in Volume 3. The Consultation and Cooperation (C & C) Agreement (K_d=0) is considered through a separate sensitivity analysis in Volume 4. In addition, the WIPP test plan now includes retardation experiments.

COMMENT 15. Page IV-1, Lines 4-8: Estimates of scenario probabilities for PA are to be made from expert judgement, but are the estimates to be made in a deterministic manner, or will a distribution from which to sample by LHS be constructed? It is not clear in this report whether future PA's will continue to use assigned probabilities for scenarios, or whether LHS sampling will be performed for this parameter as noted in the CCDF demonstration in Chapter 3. If the latter is the case, then a methodology for this approach should also be presented in this report including how the experts will be involved in making this determination.

RESPONSE: A summary of the results of the expert panel on inadvertent human intrusion into the WIPP is in Volume 1, Chapter 4 of SAND91-0893. The findings of this expert panel are in the recently published *Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant* (SAND90-3063) (Hora et al., 1991). The panel's findings were not incorporated in the 1991 calculations. In the interim, performance assessments have assumed that intrusion is a Poisson process (random in space and time) and sampled on the rate constant (see Chapter 4, Volume 1 of SAND91-0893).

COMMENT 16. Page IV-8, Lines 23-26: Comments on use of mean CCDF included in Chapter 3: it is not clear why other analysis parameters should not also be included.

RESPONSE: The full range of information generated from the performance assessments will be provided in the presentation of CCDFs for preliminary and final comparisons to the Standard.

COMMENT 17. Page IV-13, Lines 21-45; Page IV-14, Lines 1-27: The PA's in this report exclude subsidence (TS) and climatic-(base case) change as part of the scenarios; it is assumed that they will be included in future PA reports. A discussion on subsidence directly above the repository (not considered possible in this report) is criticized in Chapter 3, on the basis of secondary references used in making this determination. However, subsidence outside of the controlled area is retained for scenario development based on the possible formation of catchment basins for rainfall which could allow recharge to the unsaturated zone and the Culebra aquifer. This report as well as the cited reports (Hunter, SAND89-2546, 1989, Guzowski, SAND89-7149, 1990) do not discuss hydrological stresses to the WIPP area such as damming of streams or irrigation (Cranwell, SAND81-2573, 1987), although both reference this report. Cranwell discusses this topic in very general terms and refers to an example (p. 43) where an annual precipitation of 40 inches (compare WIPP at about 40 cm annually) is assumed. He also states that irrigation presupposes the presence of aquifers with sufficient yield to support that activity. A large mined aquifer, the Ogallala, which lies to the immediate north and east of

WIPP could be considered a prime candidate, providing future engineered recharge and expanded utilization of the Ogallala to include the WIPP area is necessary and feasible. Water could be transported from a high yield area of that aquifer. Also, local aquifers or dams along the Pecos River could be utilized pending increased moisture availability from a significant future change in precipitation (to be considered as part of the base case scenario) coupled with a concomitant favorable change in precipitation pattern. Cranwell (1987) limits his consideration of aquifers to those directly above a bedded salt repository. Since irrigation maximizes infiltration at the expense of surface runoff, it might be expected to significantly affect aquifer recharge. If the potential future hydrological stress scenarios due to irrigation activities near WIPP are to be discredited by PA in future reports, then its exclusion by screening should be justified, and not ignored as has been the case.

RESPONSE: The topics of subsidence directly above the panels and possible hydrologic stresses caused by the damming of streams and irrigation are rescreened and are discussed in more detail in Volume 1, Chapter 4 of SAND91-0893.

COMMENT 18. Page IV-15, Lines 14-17: The statement is made that a nuclear criticality scenario will be evaluated separately. A consultant to EEG in 1984 considered the possibility of a criticality incident in the Culebra. His findings indicate that under some conditions criticality was possible. The following summary is offered. . .

Criticality Considerations in the Culebra

Background

SC&A Incorporated performed Culebra criticality analyses for EEG in January 1984. These analyses considered various concentrations of fissionable material that might be in the Culebra dependent on the assumed solubilities in brine and in the distribution coefficient (Kd) value of the matrix. Also minerals in the water and brine were considered for their effect on moderating or poisoning a criticality event.

The analyses considered two geometries. One was a block of Culebra 7 m high x 5 m wide x 1 m long. The other size block was 7 m high x 0.5 m wide x 1 m long. Two plutonium solubilities were considered 0.66 mg/l and 6.6 mg/l (2.8E-6 M and 2.8E-5 M). A high and low value in adsorbed iron was also considered, since its concentration is fairly significant. A plutonium Kd value of 2,000 ml/g and a bulk rock specific gravity of 2.0 was assumed in all cases.

The results indicated that with the 5 m wide block and the high plutonium solubility the conditions could be very supercritical. For the 0.5 m wide block and high plutonium solubility the values are slightly subcritical or slightly critical. EEG concurred (in an 8/10/84 letter from Neill to W. R. Cooper) that if the plutonium solubility limit in the repository did not significantly exceed 0.66 mg/l there should not be a credible accumulation of fissile material outside of the repository that would lead to a critical configuration. Also implicit in this conclusion was that the Kd value would not significantly exceed 2,000 ml/g.

The possibility of a criticality event in the Culebra needs to be re-examined because of the possibility that both the plutonium solubility and Kd values could be greater than those used in the low fissile case.

Solubility

At present the performance assessment is assuming that solubilities could be as high as 1 E-3 M. This is 35 times the high fissile value used by SC&A. It would undoubtedly lead to k_{eff} values greater than 1.0 for all conditions evaluated. Even for 1E-4 M solubility most of the high fissile conditions would be supercritical (exception perhaps for Case C).

Kd Values

A variety of plutonium Kd values have been used. Table A-8 in Appendix A of SAND89-2408 [Rechard et al., 1990] uses 100 ml/g as the expected value for the matrix while Siegel (in a 6/12/90 memorandum that is also in Appendix A) used matrix Kd values ranging from zero (0%) to 6,000 ml/g at the 100 percentile. So, Kd values might be more or less than the 2,000 ml/g value used in the SC&A calculations.

Product of Solubility and Kd

For a given volume of aquifer the important parameter for evaluating criticality is the product of solubility and Kd since this determines the amount of plutonium in the volume with assumptions used in the SC&A calculations. A value of: KdS = 2,000 ml/g (2.8 E-5 moles/l) = 0.056 ml/g (moles/l Pu) always has a $k_{eff} > 1.0$ in a 7 m x 5 m x 1 m volume and the k_{eff} is "about 1.0" (plus or minus) in a 7 m x 0.5 m x 1.0 m volume. The 0.5 m width is probably more reasonable for a scenario where the contaminated brine is injected into the Culebra aquifer from a borehole. Therefore, criticality should be re-evaluated in the future if there is ever an indication that the KdS value exceeds about 0.05 ml/g (moles/l).

Conclusion

A 1984 analysis performed by SC&A, Inc., for EEG indicated that a criticality event in the Culebra aquifer from adsorbed plutonium following a release from the repository was not credible with the maximum values of plutonium solubility and Kd that were believed to be appropriate at the time.

Recent studies related to the Performance Assessment suggest that the solubility of plutonium in brine could be two orders of magnitude greater than that assumed in the "non-credible" determination. Also, the Kd value could be higher than the value used by SC&A, Inc.

The criticality issue needs to be thoroughly re-evaluated if Performance Assessment data indicates that the product of KdS might exceed about 0.05 ml/g (moles/l of plutonium).

RESPONSE: A performance-assessment task has been initiated to examine the potential for nuclear criticality from post-closure processes.

COMMENT 19. EEG Views on Scenarios and Assumptions Considered by Sandia [SNL] in Preliminary Performance Assessment: Analyses by Arthur D. Little (ADL), SC&A, and by EEG over the years lead to several questions about the completeness of Sandia's scenarios and the detailed assumptions used.

Parameter Uncertainty

Sandia has reached conclusions about several parameters where uncertainty exists that have had significant effects on scenarios considered, detailed assumptions made and in outcome of analyses. The parameters are discussed below.

19a. Marker Bed - 139 (MB-139) Permeability. The characteristics of MB-139 are very important in any realistic modeling of the repository room horizon. There is reason to believe that MB-139 will be the most effective conduit between waste storage rooms and: other rooms, other panels, repository shafts, and the accessible environment. ADL assumed that a disturbed area in MB-139 will extend out 50 feet horizontally from mined waste storage rooms and that this area will be in hydraulic and pressure communication with waste storage rooms. This assumption increases the sensitive area of the repository to a human intrusion drill bit by a factor of 4.4. Also, the permeability values chosen for MB-139 in both the near-field and far-field affect results in a number of undisturbed and disturbed scenarios.

EEG believes that Sandia should include a MB-139 disturbed area in the surface area available for all human intrusion scenarios unless there is field data to indicate that the disturbed area will not be in communication with waste storage rooms. Also the distance that the disturbed zone extends from waste storage rooms should be estimated from actual field data.

RESPONSE: The extent of the Disturbed Rock Zone (DRZ) in MB139 is an important factor in answering the question of whether exploratory boreholes near (0-50 m) the WIPP repository are in effective communication with the waste storage rooms through MB139. Following mining, an ellipsoidal pattern of fractures develops around the excavations. An arcuate fracture system concave toward the opening develops in the floor and roof. This DRZ varies in size and depth (1 m-5 m) (3 ft-16 ft) according to the size and age of the opening (Lappin et al., 1989). The DRZ generally extends far enough to include the MB139 directly below the repository. Currently, there is little evidence that the DRZ exists beneath unexcavated portions of the underground workings (Stormont et al. 1987).

The lack of a DRZ below unexcavated portions of the repository suggests that an intruding borehole outside the boundary of the repository would not be in effective communication for radionuclide transport in quantities important for CCDF construction with the repository wastes. This hypothesis was examined by Stormont et al. (1987) in SAND87-0176.

The principal pathway for radionuclides out of a pressurized repository is downward into MB139 and then laterally outward in MB139. If the resistance to flow of the small thickness of DRZ between MB139 and the repository is neglected, it can be assumed for computational purposes that the repository wastes lie entirely within MB139. Because excavation damage exists in MB139 only directly under the waste rooms, the permeability of MB139 beneath the rooms will be greater than MB139 regions away from the repository.

If a borehole penetrates a pressurized, brine-saturated repository panel (and in this model MB139), brine would be expected to flow into the borehole at a rate determined by the local permeability adjacent to the hole and the pressure gradient.

In the following calculations using the code SUTRA, the brine flow rates into hypothetical boreholes are calculated as a function of borehole location. Boreholes penetrating the repository and at various distances away from the repository are considered.

Spatial Grid

The analysis used the fine mesh Finite Element (FE) model used in the repository modeling of undisturbed conditions for one-phase flow and transport (Volume 2, Chapter 4 of SAND91-0893). In order to accurately model a borehole near the repository boundary, the FE mesh had to be grossly refined where simulation boreholes were to be placed. The mesh utilized symmetry and areal geometry to represent one-fourth of the WIPP repository's shadow projected onto the MB139 layer. Thus, the "footprint" of the repository on the MB139 medium was represented as material MB139DRZ, and the surrounding material was denoted as MB139FF (Far-Field). The final mesh used in the analysis consisted of 4740 elements (79 x 60 elements, and 80 x 61 nodes), shown in Figure 1. Thickness of all elements (normal to the plane) were assigned a value of 1.0 m. Simulation boreholes were then assigned to nodes located at 0.25, 0.50, 1.00, 2.00, and 1710.80 m outside the MB139DRZ, lying inside material MB139FF between the repository's footprint "toes." In addition, boreholes were modeled on the interface of MB139FF/MB139DRZ, at 0.25 m inside material MB139DRZ, and along the axis of symmetry of the FE mesh (74.00 m from the MB139FF/MB139DRZ material boundary). Simulation borehole nodes in the vicinity of interest are depicted in Figure 2.

Material Properties and Boundary Conditions

The required SUTRA flow equation properties are grain density (of solid matrix), fluid density, permeability (assumed isotropic for this calculation), bulk compressibility (of solid matrix), and fluid compressibility. Both materials' property values are listed in Table 1. Dirichlet boundary conditions (p = 11.0 MPa) for the grid were applied to the far-field boundaries. Neumann boundary conditions ($\partial p_f/\partial u = 0$; where u = outward normal direction) were applied to the one-fourth repository/MB139 symmetric boundaries, as shown in Figure 3. To simulate boreholes, a pressure of 6.5 MPa (hydrostatic) was assigned to a borehole node. The FE mesh was refined such that all elements surrounding borehole nodes were square and had a length of 0.25 m. Thus, all simulation boreholes had an effective diameter on the order of 0.25 m, as shown in Figure 4.

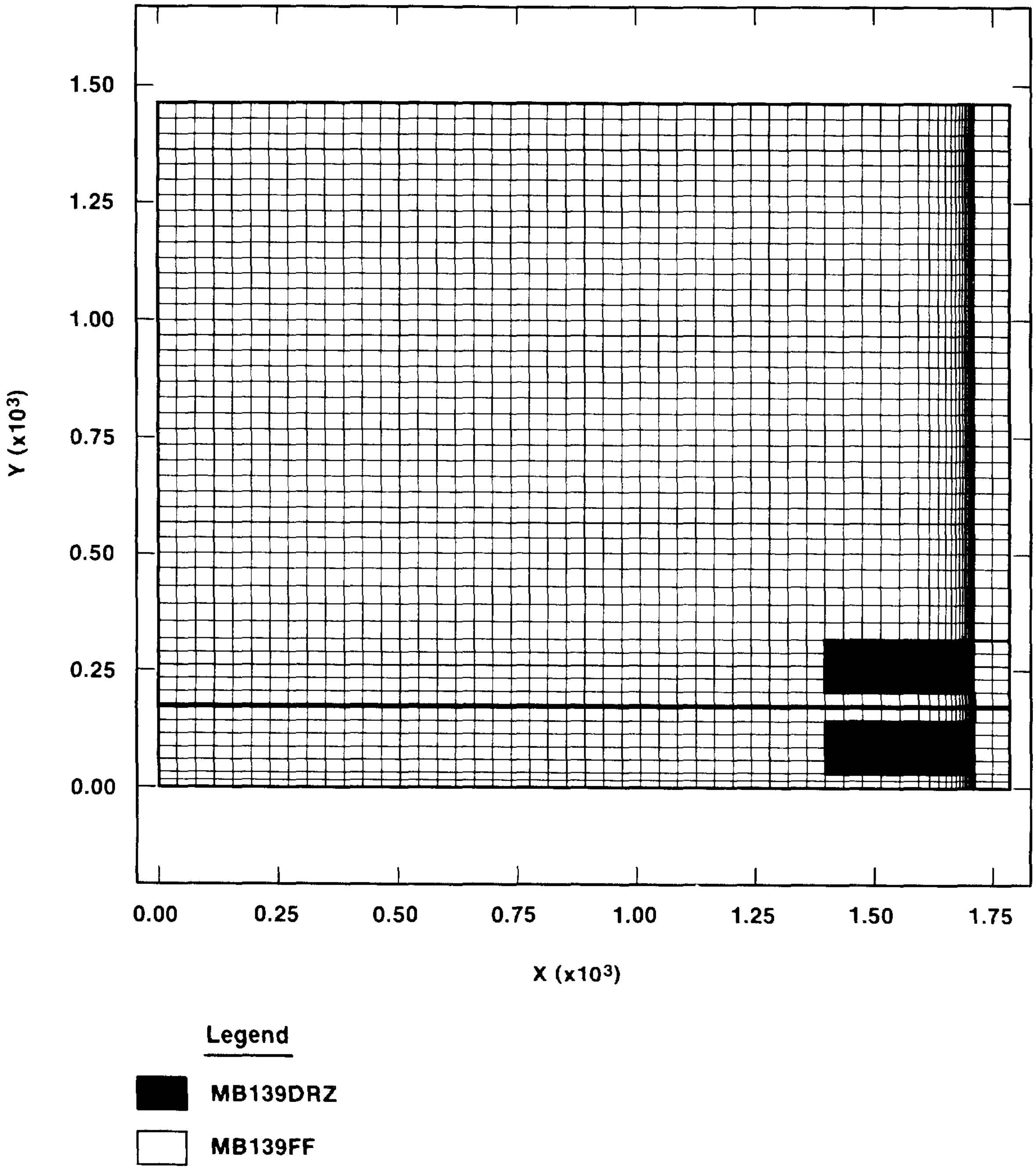

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Figure 1. Final FE Mesh Used in Modeling of Undisturbed Conditions.

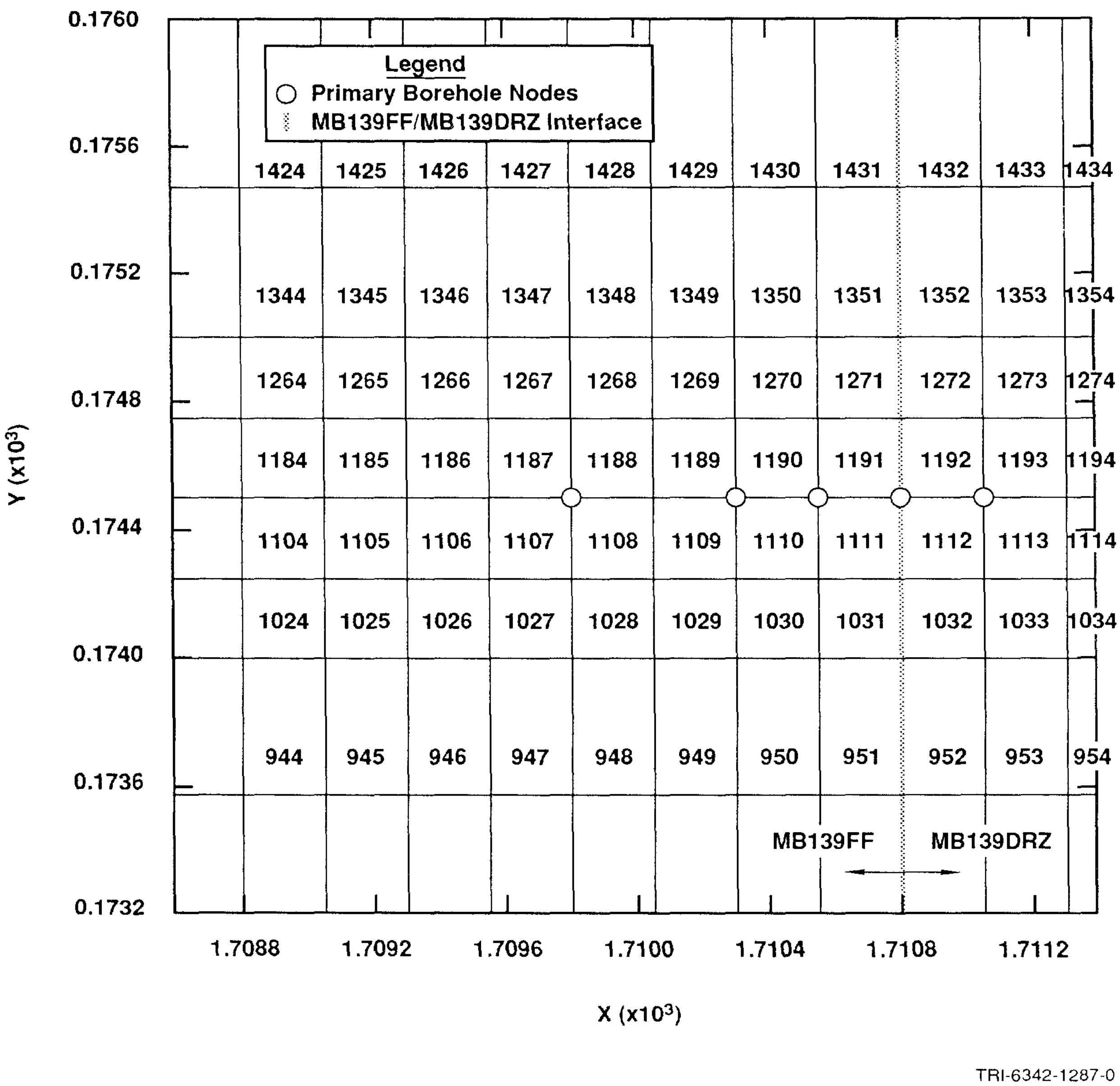


Figure 2. Simulation Borehole Nodes near the MB139FF/MB139DRZ Material Boundary.

TABLE 1. MATERIAL PROPERTIES USED FOR ONE-PHASE FLOW AND TRANSPORT CALCULATIONS

Material	Property	Value
MB139FF	Grain Density	2.963E+03 kg/m^3
	Permeability	2.870E-20 m^2
	Porosity	1.000E-02
	Bulk Compressibility	1.200E-11 Pa^{-1}
	Fluid Compressibility	2.700E-10 Pa^{-1}
	Fluid Viscosity	1.600E-03 Pa-s
MB139DRZ	Grain Density	2.963E+03 kg/m^3
	Fluid Density	1.200E+03 kg/m^3
	Permeability	1.000E-17 m^2
	Porosity	5.500E-02
	Bulk Compressibility	1.200E-11 Pa^{-1}
	Fluid Compressibility	2.700E-10 Pa^{-1}
	Fluid Viscosity	1.600E-03 Pa-s

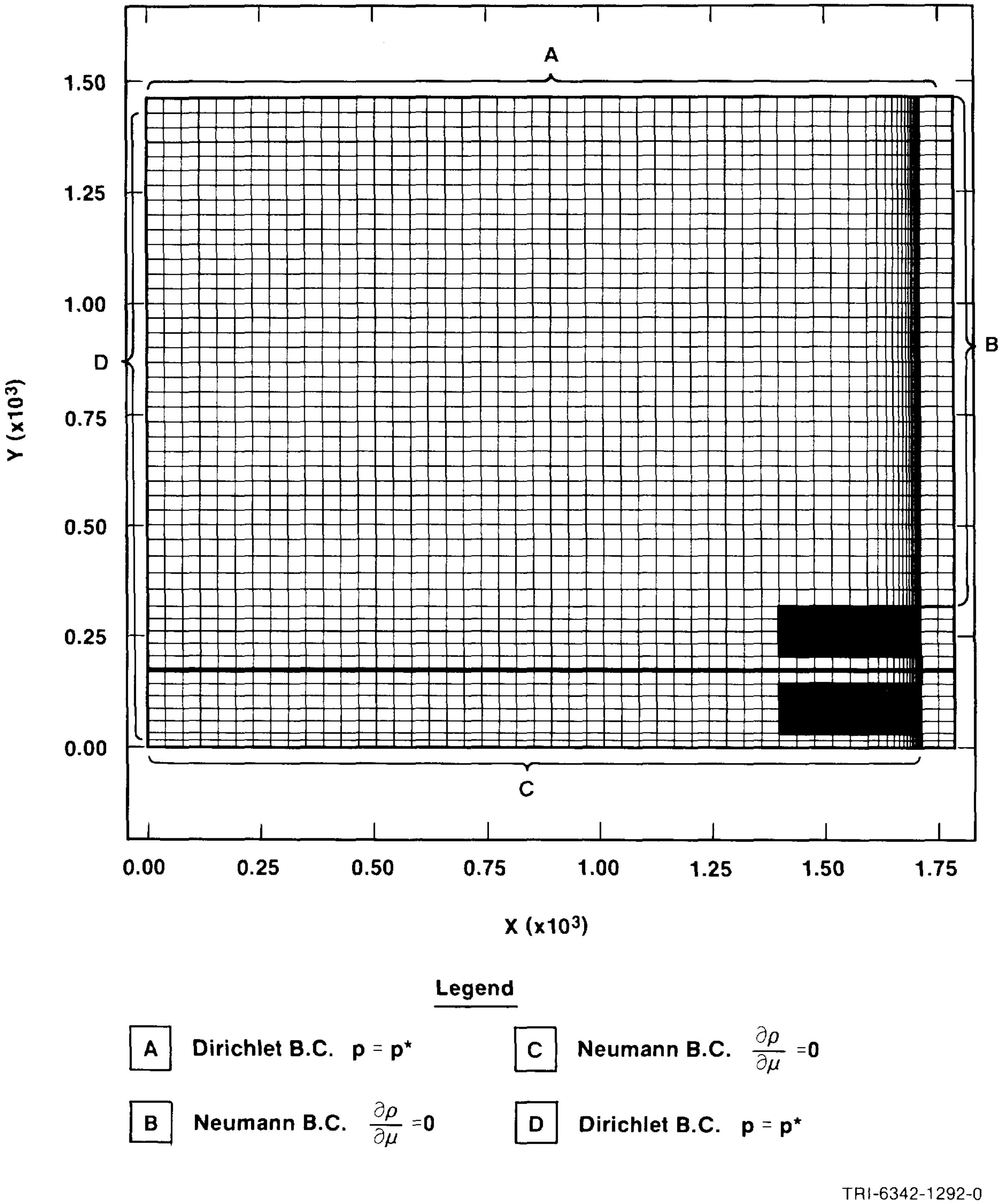


Figure 3. Application of Dirichlet and Neumann Boundary Conditions to the One-fourth Repository/MB139 Symmetric Boundaries.

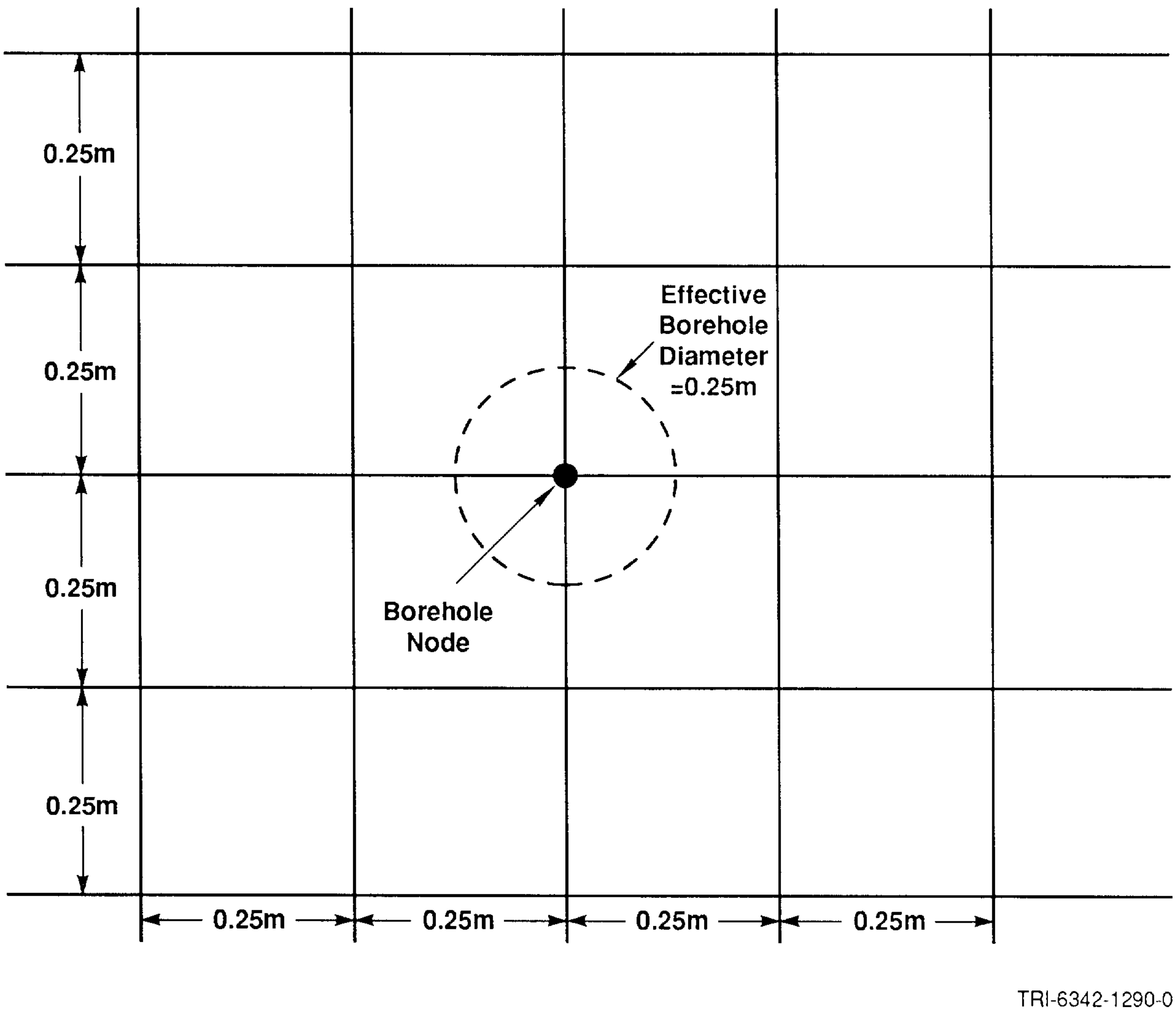


Figure 4. Effective Diameter of Simulation Boreholes.

Results and Discussion

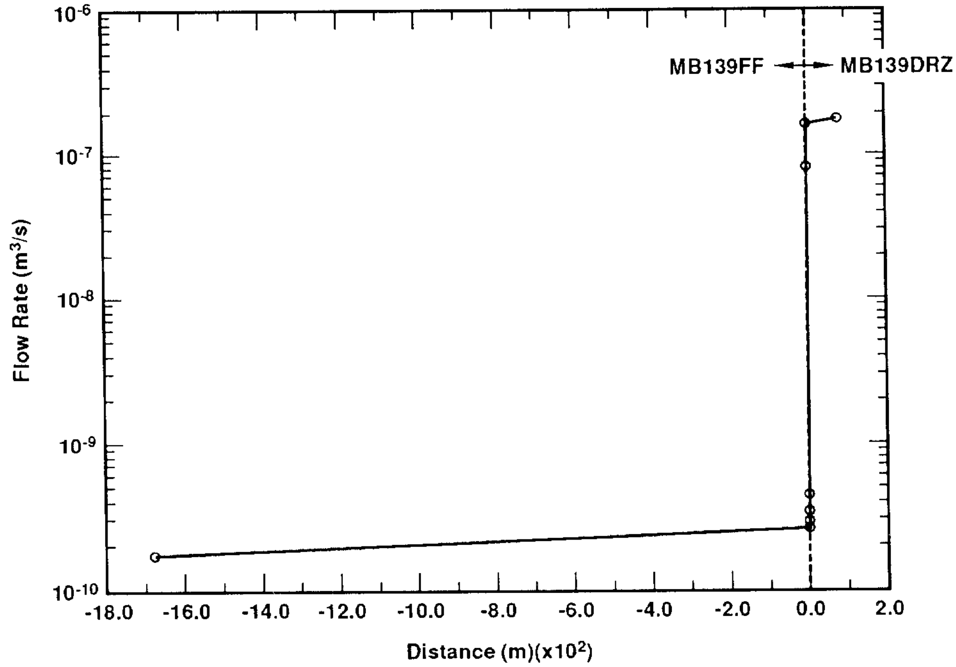
The undisturbed calculations (Volume 2 of SAND91-0893) involving transient flow and transport into the MB139 medium used a time-varying source term, applied to interior nodes within material MB139DRZ, and was run to 10,000 years. Due to the mesh refinements in the current model, numerical stability required a very small time step. Thus to maximize computational efficiency, steady-state calculations were implemented. Instead of applying a time-varying pressure function, representing gas generation within the repository, a constant pressure of 18 MPa was used as the source term driving the fluid flow. Since transport was of no interest, the transport equations were turned off during the calculations. Therefore, seven steady-state calculations were run, a separate calculation for each borehole at a unique spatial location.

As seen in Figures 5a and 5b, the simulation borehole flow rates change dramatically as boreholes are placed outside of the "footprint" of the repository. In Figures 5a and 5b, the negative distances represent the borehole locations measured from the MB139FF/MB139DRZ interface, residing within material MB139FF. Similarly, positive distances represent the borehole locations measured from the MB139FF/MB139DRZ interface, within material MB139DRZ (i.e., the repository's "footprint"). In these figures, the flow rates represent the amount of fluid flowing into a borehole node, simulating the amount of fluid flowing up (normal to the plane of the MB139 medium) a borehole. Viewing Figure 5b, it can be seen that the simulation borehole flow rates drop approximately two and one-half orders of magnitude from inside the repository's "footprint" (MB139DRZ) to outside the "footprint" (MB139FF). Specifically, just 0.25 m inside the MB139FF/MB139DRZ interface (distance 0.25 m, node 1193), the approximated steady-state flow rate was 1.78E-07 m^3/s, and just 0.25 m outside the MB139FF/MB139DRZ interface (distance -0.25 m, node 1191), the calculated steady-state flow rate was 4.89E-10 m^3/s.

Conclusions

Based on this analysis, it seems unnecessary to enlarge the effective repository area for disturbed scenario compliance calculations to include near "hit" situations. As demonstrated by these calculations, boreholes striking outside the repository experience a significant (two orders of magnitude) decrease in volumetric flow rate.

19b. Permeability in Shaft and Borehole Seals. The appropriate value for expected and degraded permeability values in WIPP shafts and boreholes is important to the determination of whether the release to the accessible environment modeled by ADL in the undisturbed case is plausible. Also, high permeability values could influence the reasonableness and consequences of the U-Tube Scenario (Magenta - repository - Culebra) considered by SC&A.



a.

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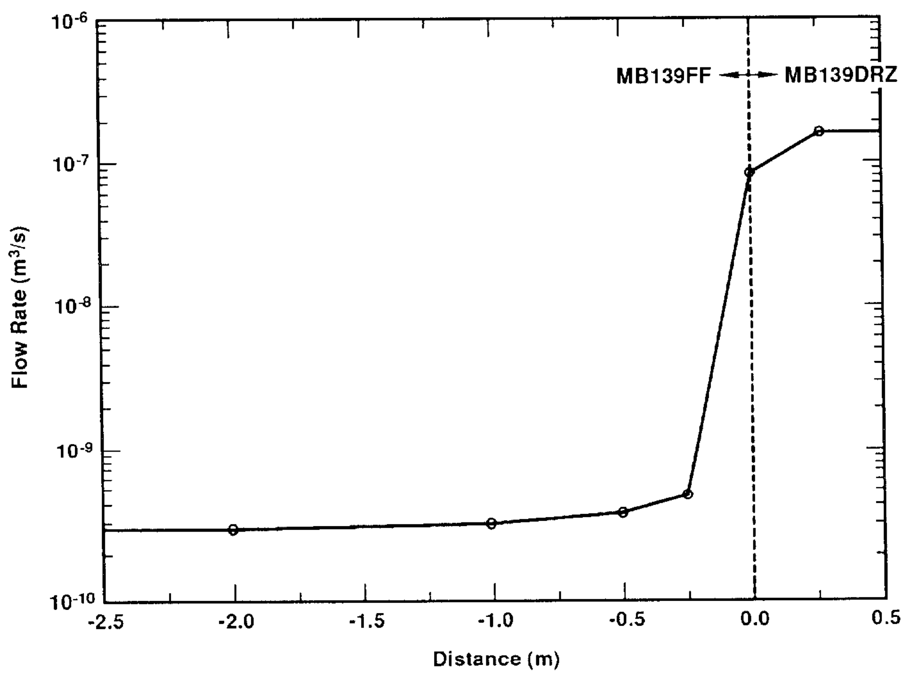

b.

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Figure 5. Borehole Flow Rates versus Distance of MB139DRZ.

EEG believes that Sandia needs to justify any shaft permeability values used in any disturbed or undisturbed scenarios.

RESPONSE: The shaft backfill is an engineered barrier; consequently, the permeabilities can be specified in designs (Nowak et al., 1990). As shown in Volume 2 of SAND91-0893, the current design specifications limit the maximum allowable shaft permeability below those assumed by PA for simulating long-term performance. Justification depends on the outcome of the seal test program. Seal requirements for demonstrating compliance are discussed in Volume 4 of SAND91-0893.

19c. Climate Change. Climate change is ruled out as a variable by concluding that rainfall in a pluvial period was only double that in recent history. This estimated increase may be a reasonable conclusion from the data (EEG has not evaluated this). However, a doubling of annual precipitation is likely to lead to somewhat greater than twice the annual recharge.

A more detailed evaluation of possible recharge and Culebra transport is necessary before it can be concluded that the effects of climatic change are negligible.

RESPONSE: Climate change has not been ruled out as a variable, nor is the present understanding of the relationship between climatic change and recharge adequate to conclude that the effects of climatic change are negligible. Doubling of annual precipitation is likely to result in substantially larger increases in infiltration (see memo by Swift in Volume 3 of SAND91-0893). The 1991 groundwater-flow model does not directly link changes in infiltration to changes in model boundary flux. Instead, increased recharge was simulated by prescribing elevated heads along the northern boundary of the model domain (see Volume 1, Section 5.1.9 of SAND91-0893).

19d. Subsidence and Surface Recharge. Actions by humans have the potential to significantly increase recharge. Potash mining either within or outside the WIPP Site boundary could lead to a pathway for Culebra recharge, even without a pluvial period. Also, the present Memorandum of Understanding between the Department of Energy and the Bureau of Land Management in conjunction with the Administrative Land Withdrawal in January 1991 allows BLM to sell or give away sand, gravel, and caliche from the surface of the WIPP site (including the exclusive use area above the wastes).

These other possibilities of enhanced recharge to the Culebra need to be seriously considered in scenario assumptions.

RESPONSE: The effects of subsidence related to potash mining have been included in scenario development but are not yet sufficiently well understood to be incorporated in consequence modeling. Effects of subsidence on groundwater flow in the Culebra will be modeled in future performance assessments.

The effects of near-surface activities (e.g., removal of caliche) on flow in the Culebra have not been evaluated, but because units above the Culebra have low permeabilities at and near the WIPP, the potential for a significant change is believed to be small. The effects of vertical flux into the Culebra within the model domain, regardless of the hypothesized cause, will be evaluated in future simulations of groundwater flow.

19e. <u>Uncertainty in Radionuclide Source Term</u>. There is some uncertainty in the volume, number of curies, and radionuclide composition of the wastes that will eventually be brought to WIPP for disposal. All of these parameters will have some effect on the CCDF. It is realized that the WIPP Project [Site] Office is continually refining and updating data on the existing and not-yet-generated waste.

The amount of heat-source wastes (Pu-238) that will come to WIPP as well as the waste form and number of curies per container could be especially important to performance assessment calculations. About 80% of the total alpha-TRU radioactivity presently projected to be emplaced in WIPP is Pu-238 and of this total over 95% is in heat source wastes at SRS or LANL. This large amount of radioactivity greatly increases the multiplier for Table 1, thus greatly increasing the quantity of radioactivity that is allowed to reach the accessible environment.

Since Pu-238 has a half-life of only 87.7 years it figures to be of much less concern per curie during the 10,000 year evaluation period than U-233, Pu-239, Pu-240, and Am-241. Thus, the presence of heat source wastes would be expected to make compliance with 191.13 easier.

Most of the present Pu-238 wastes cannot be shipped to WIPP with the current NRC certificate of compliance for TRUPACT-II and may never be shippable without treatment. Since DOE has made no firm commitments concerning treatment of heat source wastes there is an uncertainty about whether the waste will come to WIPP at all, and (if it does come) in what form.

Sandia should perform PA calculations and plot a CCDF for two source term conditions, one with the heat source waste included and one without.

RESPONSE: Performance Assessment has considered the suggestion made by the EEG to look at inventories with and without heat-source Pu wastes. In all 1991 calculations, the WIPP is assumed to be filled to the design volume, with quantities of radionuclides scaled up from the 1990 IDB. Using a smaller inventory (without the Pu-238 in heat-source waste) would result in smaller allowable releases.

Pu-238 is <u>not</u> "of much less concern during the 10,000-year evaluation period than U-233, Pu-239, Pu-240, and Am-241" because Pu-238 decays to Pb-210 through the three daughter products U-234, Th-230, and Ra-226. "Thus, the presence of heat-source wastes would be expected to make compliance with 191.13 easier" only if the daughter products of Pu-238 are ignored. The Standard requires the consideration of decay products, and performance assessments therefore consider the complete design inventory.

Comment 19 (continued). <u>Scenarios Not Considered</u>

At the present time Sandia is not assuming that any radionuclides will be brought to the surface except in drill bit cuttings from the "effective" radius of the borehole. Furthermore, it is assumed that all wastes in drill bit cuttings contain only average concentrations of radionuclides.

Waste being brought to the surface has the potential to be a more severe test of the Standard than having the waste diverted into the Culebra Aquifer where transport to the accessible environment can be significantly delayed by ground water flow time and retardation factors. Yet at the present time Sandia has eliminated all scenarios where wastes are brought to the surface except as drill bit cuttings. The deletion of discharges to the surface is unrealistic and non-conservative.

In 1987 Sandia performed scoping and preliminary PA calculations where they considered volumes of radioactive material that might be brought to the surface from drilling into waste storage rooms in the following conditions:

(a) containing a brine slurry;
(b) in dry consolidated form;
(c) in dry nonconsolidated form.

These deterministic calculations indicated that the quantities of radioactivity brought to the surface could exceed the [EPA] standard in cases (a) and (c).

The uncertainty in waste storage room conditions reflected in Sandia's 1987 work still exists. The primary problem is that if room closure and consolidation cannot be guaranteed before brine inflow occurs and/or the 100 year control period expires then conditions (a) or (c) could be present at the time of intrusion. In 1987 the point was made that early reduction of void space alone might solve this problem. Yet, no progress has been reported in confirming this preliminary finding or in reducing void space by waste modification and/or backfill design changes.

EEG believes that Sandia must consider releases of radioactive material to the surface beyond the average radionuclide composition drill bit cuttings included in the Preliminary Comparison. Our concerns are expressed in more detail below.

Radionuclide Quantities in Drill Cuttings. The scenarios recognize there will be radioactive material brought to the surface in drilling fluid each time waste storage rooms are penetrated. This material will be both from drill bit cuttings and from "cavings" (additional material "eroded from the walls of the borehole at the repository horizon by the circulating fluid.") SAND90-2347 (pages V-83 to V-85) discusses variation in drill bit radius (is sampled probabilistically) and in shear strength of the waste which affects the amount of "cavings" (which is being studied). EEG agrees with the procedure being used to determine the final hole radius, but we point out that the bulk shear strength of the waste should also be considered for those cases where the waste is unconsolidated or in a brine slurry. The 1987 scoping studies assumed that in a dry non-consolidated room all waste in an intercepted drum would be carried to the surface and in a brine slurry room that 46 m^3 of brine would flow to the surface. These assumptions are reasonable and a good starting point for developing waste volume distributions.

The average radionuclide composition and concentration varies significantly between waste generation sites. Also, there is considerable variation between waste packages at each site. Unlike spent fuel in a high-level waste repository there is no average or typical TRU waste container. Table [2] (developed from data in DOE/RW-0006, Rev. 6, the 1990 Integrated Data Base [U.S. DOE, 1990a]) indicates the estimated averages of presently stored and newly generated wastes at the individual generating sites.

The variation at each generating site is also significant. For example, the Savannah River Site (SRS) is expected to have 5,560 drums averaging 880 Ci/m^3 (DOE/WIPP 88-005 [U.S. DOE, 1989]). Since drilling into waste is an expected event and the EPA standard requires that releases with an expected probability greater than 0.001 be considered, it is necessary that cuttings from the more concentrated packages be considered.

TABLE 2. PERCENT VOLUMES AND AVERAGE CONCENTRATIONS FROM TRU WASTES GENERATING SITES

Generator	Volume Percent	Cumulative Percent	Average Concentration (Ci/m^3)
NTS	0.6	0.6	1.17
LLNL	1.1	1.7	2.09
Mound	0.9	2.6	2.36
RFP	16.0	18.6	3.69
ANL-E	0.2	18.8	3.94
INEL	39.5	58.3	4.89
Hanford	10.3	68.6	5.28
ORNL	1.2	69.8	24.92
LANL	11.4	81.2	54.51
SRS	18.7	99.9	181.07

Ref: DOE/RW--0006, Rev. 6 [U.S. DOE, 1990a]

The effect of considering the high concentration packages in the current calculations is believed to be significant. From the CCDF plots in Figures VI-2, 3, 4 (in SAND90-2347) it appears that the quantities released during drilling are about 2 to 4 curies. This is approximately the value EEG obtained using average container concentrations and a 12 inch effective diameter borehole. However, we believe that when the SRS high-curie containers are considered there could be greater than 30 curies brought to the surface with a probability of greater than 0.001 when considering random emplacement (which may not be the actual or the most conservative mode). We recommend that this variation in radionuclide concentrations be determined as well as possible and treated probabilistically in the calculation.

RESPONSE: The analyses summarized by Lappin et al. (1989) indicated that a brine slurry would not form in a gas-free repository. The two-phase BRAGFLO calculations conducted for this report (see Volume 2 of SAND91-0893) support this conclusion: the presence of gas results in less brine in the waste. The effective shear strengths for erosion currently being used in cuttings calculations are very low, on the order of 1 Pa.

The possibility of waste removal through a borehole from a gas-pressurized and gas-saturated repository with consolidated or unconsolidated wastes is currently under study.

Comment 19 (continued). Contaminated Brine Flows to the Surface. The El, E2, and ElE2 scenarios assume that the only material reaching the surface is from drill bit cuttings and some "cavings" from the annulus about the drill bit in the waste storage room. Brine flowing to the surface from an encounter with a pressurized Castile brine reservoir was not assumed. EEG believes that brine flows to the surface should be assumed and that the consequences could be significant for the ElE2 scenario. Our reasons follow.

Sandia and DOE have described typical drilling practices elsewhere (Appendix C of SAND89-0462 [Lappin et al., 1989] and in DOE February 7, 1990 response to EEG's comments on the Draft Supplement EIS). These responses explain how it is possible to have very little flow to the surface by closing in blow-out preventers within a few minutes, determining the pressure, and then preparing drilling mud of sufficient density to stop the flow before resuming drilling. For example, it was stated (in the 2/7/90 letter) that only 51 barrels flowed at WIPP-12 before shut in by a blow-out preventer.

The 2/7/90 DOE letter went on to say that at WIPP-12 an additional 49,224 barrels flowed during deepening, geophysical logging, and further deepening before it was finally shut in for subsequent hydrologic testing. This additional flow was described as resulting from a "conscious decision."

It appears that virtually every time a pressurized Castile brine reservoir has been encountered in the vicinity of WIPP that "conscious decisions" have been made to allow varying amounts of brine to flow at the surface. Table [3] extracted from two WIPP reports (TME-3080 and TME-3153) [U.S. DOE, 1981 and U.S. DOE, 1983] describes remedial measures taken. Although the available data are not as detailed or as quantitative as one would like, it is clear that drilling practice through 1982 included release of brine at the surface whenever pressurized Castile brine reservoirs were encountered. In the absence of any brine reservoir encountered in the Delaware Basin since 1982, where new practices might have been observed, we believe that typical commercial drilling practices should be assumed.

Brine released at the surface from the E2 scenario would be expected to increase the effective radius of the borehole and thus increase the amount of waste brought to the surface in suspension and in solution. The major effect could occur in the ElE2 scenario because brine present in the repository from the first encounter (which would be expected to be saturated in uranium, plutonium, and americium) would be discharged at the surface. The following example indicates that discharge could be significant.

There would be about 8,800 m^3 of brine in a waste panel if 20% of the original volume contained brine. If plutonium, americium, and uranium were present in the brine at 10^{-6} Molar concentration there would be about 8,000 Ci at 150

TABLE 3. CASTILE BRINE RESERVOIR INTERACTIONS IN WIPP AREA

Name of Well	Date Drilled	Initial Flow bbl/day	Remedial Action
Mascho-1	1937	8,000	No action to stop flow.
Mascho-2	1938	3,000	No action to stop flow.
Culbertson-1	1945		3,000 barrels estimated to flow to surface. No record of flow rate or duration.
Tidewater	1962	NA	12 pound per gallon drilling mud did not stop. Finally control by casing and cementing.
Shell	1964	20,000	Allowed to flow until artesian flow ceased.
Belco	1974	12,000	Brine flowed to surface for 26 hours with 14 pound per gallon drilling mud.
Gulf	1975	5,000	No records on total volume or duration of artesian flow.
ERDA-6	1975 1981-82 (testing)	660	WIPP borehole. Estimate 19,000 barrels could be produced by artesian flow.
Pogo	1979	10,000	Initial flow of 1440 bbl/day with 14.6 pound per gallon drilling mud. Stopped after 4 days with 15 pound per gallon mud.
WIPP-12	1981	12,000	WIPP borehole. Over 79,000 barrels produced. Estimate 350,000 barrels producible by artesian flow.

References

- U.S. DOE Brine Pocket Occurrences in the Castile Formation, southeastern New Mexico, TME-3080, March 1981.
- Brine Reservoirs in the Castile Formation Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico, TME-3153, March 1983.

years after closure, 6,700 Ci at 1,500 years, and 800 Ci at 3,000 years. Permissible quantities of waste allowed in the accessible environment (assume 10 times Table 1 values) would be between about 1,700 and 5,100 Ci depending on the TRU waste equivalency definition finally used.

Although the hydraulic characteristics of many brine reservoirs are adequate to flow 8,800 m^3 at the surface (WIPP-12 would have flowed 56,000 m^3), the amount of brine flowing from a panel might be somewhat less. However, the solubility could be somewhat higher. The solubility of americium is particularly important because of its high specific activity. At 10^{-6} M americium-241 contributes about 90%, 98%, and 79% of the total activity at 150, 1500, and 3000 years. The quantities in solution are solubility limited before about 1,500 years (at 10^{-6} M) and inventory limited thereafter.

EEG believes that the Performance Assessment has to include events where contaminated brine comes to the surface. Computational details would determine whether these events should be incorporated into the E1E2 scenario or into a separate scenario.

RESPONSE: The EEG raised the question of increased quantities of waste being brought directly to the surface if flow from a penetrated brine pocket was allowed to continue unrestricted. This could happen by two mechanisms. First, some additional particulate waste could be eroded from the borehole wall. Second, waste dissolved in brine within the panel could be brought to the surface with the Castile brine. The first mechanism has been examined with calculations discussed in the next paragraph. The second mechanism, which requires an E1E2-type intrusion and flow of Castile brine through the panel, has not been modeled. It can be noted qualitatively, however, that because of the resistance provided by the relatively low-permeability waste and backfill, flow along the E1E2 pathway is less likely to result in an uncontrolled flow of brine at the surface.

The first mechanism has been examined with a CUTTINGS calculation to assess the importance on erosion of unrestricted brine flow from a Castile brine pocket in an E1 scenario. Unrestricted artesian flow from a Castile brine pocket would normally not be permitted. However, several cases of such flow have occurred in past drilling events near the WIPP site. In 1964 a well (Shell) was allowed to flow to the surface until artesian flow ceased. The initial flow rate was 20,000 bbl/day. Using this value of brine flow, borehole erosion was calculated with the CUTTINGS code assuming that the drill bit had passed the repository horizon and penetrated a Castile brine pocket. The uphole flow rate was assumed to consist of the combined drilling mud flow and brine pocket flow. The drill diameter adjacent to the repository was also assumed to be the outside drill stem diameter. All other input parameters were kept the same (see Table 4). The results indicate that for the chosen input variables, there would be an increase in the volume of waste transported to the surface of 19.6%.

TABLE 4. INPUT AND OUTPUT VARIABLES-CUTTINGS

	With Castile Brine Flow	Without Castile Brine Flow
Drill String		
Angular Velocity	7.7 rad/s	7.7 rad/s
Diameter of Intrusion		
Drill Bit	0.4444 m	0.4444 m
Relative Roughness	0.25	0.25
Effective Shear Strength		
for Erosion	1 Pa	1 Pa
Fluid Density (Mud)	1200 kg/m^3	1200 kg/m^3
Viscosity	9.17×10^{-3} Pa•s	9.17×10^{-3} Pa•s
Yield Stress Point	4 Pa	4 Pa
Drill String Diameter	0.1016 m	0.1016 m
Mud and Brine Flow Rate	8.094×10^{-2} m^3/s	4.415×10^{-2} m^3/s
Final Eroded Diameter	1.0866 m	0.9935 m

Comment 19 (continued). Brine Slurry Filled Room. A brine slurry filled room could be present in scenarios that do not involve a brine reservoir. Also, because of creep closure and gas generation this brine could be under greater than hydrostatic pressure and thus have a driving force of its own (unless the gas cap was relieved by the drill bit upon initial entry to the room). The potential quantities of brine that might come to the surface would be somewhat less than with a brine reservoir (perhaps tens of cubic meters rather than hundreds or thousands of cubic meters) but the consequences could still be significant.

The brine slurry room scenario with wastes being brought to the surface in drilling fluid and/or by flow should be included unless other studies can establish that this room condition will not exist in the absence of a brine reservoir.

RESPONSE: The question of a brine-slurry-filled room was raised a number of years ago by the EEG and others. It became the impetus for extensive tests on the permeability of the Salado Formation to quantify the maximum amount of brine that could enter the repository over 10,000 years. The permeability measurements to date continue to show very low permeabilities, which prevent great quantities of brine from entering the room, which in turn precludes the possibility of forming a slurry. Furthermore, the current PA two-phase BRAGFLO code models both the gas generation and brine movement as suggested. In the vast majority of simulations of the E2 scenario with varying permeability, there is insufficient brine entering the room to even fill the pores (and results in mostly zero releases (see Volume 2 of SAND91-0893)). Consequently, the extensive discussion refuting this hypothesized condition in Lappin et al. (1989), in the FSEIS (U.S. DOE, 1990b), and elsewhere remains valid.

Comment 19 (continued). Location and Effectiveness of Borehole Seals. The present scenarios assume that borehole plugs remain intact for the 10,000 year period and thus preclude any contaminated fluid from reaching the surface. This assumption maximizes the amount of fluid that will be injected into the Culebra aquifer but it may not maximize the amount of radionuclides that reach the accessible environment from both the Culebra and surface routes. Also, the location of the plugs is different in the E1 scenario portion of the E1E2 scenario than in the other scenarios. This change may lead to conservative (higher) release rates to the accessible environment but is not explained.

The assumed borehole permeability range of 10^{-11} to 10^{-14} m^2 is in the range that Freeze and Cherry [1979] call appropriate for silty sand. This appears to be consistent with guidance in the 4/91 Draft of 40 CFR 191.

EEG does not have a position at this time on the assumptions used about the location or the 100% effectiveness of the plugs.

RESPONSE: Because no question was asked, we can only comment on the three points raised: (1) maximizing flow to the Culebra by using 100% effective plugs above the Culebra, (2) changing locations of 100% effective plugs between E1 and E1E2 summary scenarios, and (3) selection of borehole permeability.

Concerning the first point, it is Performance Assessment's intent to be conservative in placing a 100% effective plug above the Culebra to divert the flow into the Culebra. Without the plug, contaminants could move higher in the borehole but not to the surface since the pore pressure in the Salado Formation and the Castile brine pocket are not great enough to move brine to the surface through a sand-filled borehole (see Reeves et al., 1991, SAND89-7069). Lateral transport of radionuclides in subsurface units above the Culebra (e.g., the Magenta Dolomite or the Dewey Lake Red Beds) has not been modeled but is believed to be less important than transport in the Culebra because transmissivity in these units is substantially lower.

As correctly surmised by the EEG concerning the second point, changing the locations of the 100% effective plugs between the summary scenarios does produce higher releases by forcing 100% of any flow from the brine reservoir directly through the waste in the E1E2 summary scenario.

On the final comment, Performance Assessment concurs with the EEG that the assumed borehole permeability range of 10^{-11} to 10^{-14} m^2 is consistent with *40 CFR 191* as originally promulgated and the April 1991 draft.

COMMENT 20. Page V-2, Lines 6-42; Pages V-26, Line 26 to V-34, Line 6: The discussion of the Culebra and Magenta dolomites in the WIPP area infers that there is a source of aquifer recharge (North and East of the site) to these units. Furthermore, it is stated that the Magenta is possibly recharging the Culebra through fractures. Also, it is mentioned that the presence of a 3 meter thick caliche layer inhibits downward flow of moisture from supra-Rustler aquifer units. The recharge statements are in apparent contradiction to the discussion on the paleo-flow transient state postulated for the WIPP (summarized on p. V-53, figure V-19) which would exclude significant moisture of recent origin from entering these aquifers. The reference to a caliche moisture flow inhibitor from the surface to aquifers farther down is also perplexing. Is the Capitan Reef at the periphery of the Guadalupe Basin implicated as an ultimate source of recharge if infiltration from the surface is to be minimized? If so, how does one explain the "pleistocene" age of the water reported for the Culebra which would negate any significant modern recharge related to this discussion? Is the caliche layer compromised by sinkholes, boreholes, potash mining, or deliberate removal? The experiments and field studies (EEG is currently involved in one) to address these uncertainties should be referenced, and the state of "ignorance" on the subject should be clearly detailed in this report to accurately present the state of uncertainty in PA.

RESPONSE: Uncertainty remains high about the past and possible future changes in recharge and groundwater flow in the Culebra. The discussion of the topic in Volume 1, Chapter 5 of SAND91-0893 has been extensively rewritten. The impact of this uncertainty on the performance of the system will be evaluated in future analyses.

COMMENT 21. Pages V-2, Line 45 to V-4, Line 9; Pages V-37, Line 4 to V-51, Line 20: The section on long-term climate variability is well written and in sufficient detail in both describing paleo-climates at WIPP, and in forecasting future climates for this area. However, several important aspects are not considered which are of relevance to the WIPP area. The first aspect concerns the potential change of WIPP to a "dry-farming" region with a doubling of annual precipitation as discussed in a previous comment (p. IV-13, 14). The second aspect concerns the distribution of the precipitation throughout the year. This report indicates that the increased moisture will occur outside of the growing season because of the southerly displacement of the jet stream during the winter. Under these conditions the doubling of annual precipitation would not produce a linear increase in soil moisture, but with reduced potential evapotranspiration rate (p.e.t.) would create significantly longer periods of water surplus in the surrounding soils and alluvium and encourage crop irrigation practices similar to those now occurring in central California. Potentially larger surface storage of moisture in surrounding dams and lakes would also encourage the latter as would potentially larger runoff from the Pecos River and its tributaries. Conversely, if the precipitation patterns were to resemble that of the midwest US, then dry farming activity would be expected to increase and to encourage irrigational supplements to overcome periods of moisture deficit currently practiced in the mid-grass region of the Great Plains. Hence PA models addressing climatic change should incorporate precipitation patterns into the analysis and model the effect on water budgets in the WIPP area. Accompanying vegetational changes through plant succession should also be modeled to determine their effect on moisture availability and their effect on WIPP integrity.

In summary, a factor of 2 increase in rainfall at the WIPP site potentially makes possible dry-farming in the area (greater than 21 inches/year precipitation is required), or increased livestock grazing. The implications of this potential effect is not discussed nor addressed in the screening of scenario possibilities at the WIPP.

RESPONSE: Doubling of precipitation may result in substantially more than doubled infiltration (see memo by Swift in Volume 3 of SAND91-0893). The performance-assessment methodology used in 1991 for simulating this increase is preliminary, and results are applicable only to the narrowly defined conceptual model for recharge at the northern edge of the model domain (see Section 5.1.9 in Volume 1, Chapter 5 of SAND91-0893). Other conceptual models for enhanced recharge will be examined in later analyses.

The WIPP performance-assessment team does not, at present, plan to model specific possible causes of increased infiltration such as changes in plant communities. Rather, the approach will be to examine the effects of varying recharge directly, with uncertainty in the recharge factor including uncertainty in the various processes that control recharge.

COMMENT 22. Page V-5, Lines 29-33; Pages V-54, Lines 35-43 to V-56, Lines 1-11: There are several areas of concern with respect to the selection of retardation factors for the Culebra dolomite: the range of values used in preparation of the CCDF (p. C-5, this document [SAND90-2347]) ranges from 1 to 16,000 (matrix), and from 1 to 50,000 (clay/fracture) for plutonium as as provided by the "principal investigator." This presumably refers to a paper presentation by Siegel (11/19/90) in which natural uranium is the basis for a natural analog study to constrain the strength of clay/solute interactions within the Culebra Aquifer. Siegel reports retardation factors of about 1,200 for Culebra dolomite using a uniform porous-medium model, and values of about 200 for clays using the fracture flow-model. Retardation factors ranging from 200-30,000 are reported for the Palo Duro basin; however, the author states that such brines may be poor analogs for the comparatively young groundwaters of moderate salinity characteristic of the WIPP site. The latter are also under reducing conditions where uranium exists in the quadrivalent state. Siegel's paper is partly based on work by Hubbard et al. (1984) and Laul et al. (1988). Hubbard states that retardation factors greater than or equal to 40 for thorium (and indirectly for uranium) may be expected in the Palo Duro Basin based on Ra-228/Th-228 ratios observed. The uranium is again assumed to be in the quadrivalent state, and Ra-228 is considered to have a retardation factor of 1.0. Laul presents retardation factors based on U-238/Ra-226 ratios in brine ranging from about 10 to 300,000 assuming a retardation factor of 1.0 for Ra-226. Two wells, Zeeck #1 (7,140-7,172 feet deep) and J. Friemel #1 (8,168-8,204 feet deep) yielded retardation factors of about 324,000 and 132,000, respectively. Both of these wells can be considered to manifest "anoxic" or reducing environments where uranium is expected to be in the quadrivalent state. In addition, Friemel #1 yielded a retardation factor of 193,000 at another comparable depth (7,326-7,300 feet deep), again indicating a reducing environment. Laul states that wells at depths between 750 to 1,800 feet are considered to be shallow aquifers and thus may represent "oxic" or oxidizing environments. Wells ranging in depth between 750 to 2,970 feet (Zeeck #4, zone 4; Mansfield #2, Detter #2; Harman #1; and Freimel #1, zone 9) yielded retardation factor estimates between 28 to 1,897. By contrast thorium retardation factors estimated by the ratio, Ra-228/Th-228 yielded 94, 1,436, and 240 for the deep wells noted above, and a range between 70 to 870 for the shallow wells. Other wells in the study gave uranium retardation factors between 2,720 to 183,000, and thorium retardation factors between 36 to 408. The range in well depths yielding these retardation factors was between 3,100 to 7,900 feet and there was a tendency for the deepest wells to have the highest retardation factors. Furthermore, all of these wells would probably qualify as "anoxic" wells according to Laul.

It thus appears from the analysis of retardation factors based on natural-analogs U-238, Ra-226, Ra-228, and Th-228, all other conditions being met, that the Culebra at about 1,000 feet below the surface would qualify as an "oxic" aquifer and that the retardation factors estimated for these types of wells would be more applicable. The above argument suggests that a maximum retardation factor of about 2,000 should be used for plutonium if it is a radiomimetic of uranium under these conditions, or a lower maximum retardation factor of about 1,000 should be used if it mimics thorium under oxic conditions. These estimates agree well with Siegel's and Hubbard's original estimates mentioned earlier. Thus, the maximum retardation factor of 50,000 used in PA may be high by as much as a factor of 50 for the clay/fracture environment and as much as 16 for the matrix-porosity environment. Even if the Culebra is found to be "anoxic," the retardation factor would still be under 2,000 for plutonium if it mimics thorium behavior according to these analyses. It would be desirable to take measurements of the type described for the Palo Duro Basin on the Culebra aquifer to determine the redox environment and natural-analog concentration ratios.

The use of a dual porosity model in PA involving both matrix and fracture-flow incorporating retardation factors due to both is based primarily on the work of Neretnieks and Rasmussen [1984] (Water Resources Research, V. 20, No. 12). This report is based on the flow of moisture through fissured crystalline rock which is less than exact due to insufficient knowledge of fissure orientation and frequency, intersection characteristics, and variations in these properties as stated by the authors. A discussion of application of this model to the Culebra dolomite without a comparison to crystalline rock, and adequate knowledge of fracture characteristics which might limit this application is not given enough consideration in this document. A similar criticism on the estimate of maximum retardation factors in conjunction with the clay coatings on the Culebra dolomite fractures was discussed earlier.

Overall, there remains insufficient justification for using any Kd values for the Culebra aquifer in performance assessment. EEG has urged DOE since 1979 to experimentally determine a range of Kd values for various conditions in the Culebra. Unfortunately, after all these years, there is no more experimental justification than was provided in the Geological Characterization Report in 1978 [Powers et al., 1978]. This serious deficiency in the data for performance assessment should be removed as soon as possible, either through field tests as planned in 1986 or through laboratory testing, or both. In the absence of reliable experimentally obtained results, EEG will insist on the implementation of the C & C Agreement provision of taking no credit for retardation in the performance assessment calculations.

RESPONSE: Expert judgment (whether from an individual or a panel) is always necessary to develop the probability distributions for use in the modeling systems (PA data base) from the results of experiments (sorption data base). Sandia is planning column experiments to begin preliminary testing early in 1992. Until data required by the C & C Agreement is available, SNL will continue to include retardation in PA analyses in order to provide guidance to the data-acquisition work.

COMMENT 23. Page V-6, Lines 40-44; Pages V-59 to V-62, Lines 31-24: Exclusion of the calibrated model for the Culebra Dolomite as derived by LaVenue et al., (1990, in PA document) is of some concern, considering the amount of effort that has gone into this activity to date. The use of a "zone" approach has the advantage of using a simpler (and shorter running time) model than SWIFT II, but it appears to be uncalibrated, and it is not amenable to parameter and conceptual-model uncertainty analysis as well. In fact the use of the zone approach only for "interim" purposes should justify an analysis of how this methodology will impact on future CCDF analyses, and what one might infer from those presented in this report. It would appear that very little effort has gone into reconciling expected calibration biases of non-unique solutions on parameter and model uncertainties in PA when techniques such as "kriging" are utilized for tuning numerical models. It might be more fruitful to question either the necessity or possibility of reconciling such biases for PA over long time periods than to abandon a well documented, bench-marked and Culebra calibrated model (SWIFT II).

RESPONSE: The 1991 calculations use 60 different transmissivity fields, each calibrated to observed head data (see Sections 5.1.9 in Volume 1 and 6.3 in Volume 2 of SAND91-0893). A geostatistics expert group has been established to advise the performance-assessment team on suitable methods for including uncertainty in groundwater flow in future performance assessments (see Volume 2, Section 6.2 of SAND91-0893). Among the techniques being examined for use in future performance assessments is an extension of the pilot point approach of LaVenue et al. (1990), which will generate random fields conditioned on transmissivity data and both steady-state and transient head data, without restrictions on the variance of transmissivity and with the capability to include variable-density flow models (see Volume 2, Section 6.2 of SAND91-0893).

COMMENT 24. Page V-74, Lines 18-22: A reference is made to Radon-226 as the daughter of Ra-226 several times in this discussion. Radon-222 with a half-life of 3.8 days is the correct isotope of radon gas produced from Ra-226 (Radon-226 does not exist). Furthermore, it is stated that the activity of this radioactive gas will be insignificantly small. Because it will be in secular equilibrium with Ra-226, then the same reasoning will show that the activity of Ra-226 will be insignificantly small as well. The same logic would apply to the daughter products of Rn-222 including Pb-210. Was this the point of this discussion?

RESPONSE: The discussion of radon-222 as the only radioactive gas expected is correct in line 17. The reference to radon-226 in lines 20 and 21 were typographical errors. The point of the discussion was that the only gaseous radionuclide was radon-222, there was a very small quantity of it, and not including gaseous transport of volatile radionuclides would not significantly affect radionuclide releases.

Appendix B References

Cranwell, R. M., J. E. Campbell, J. C. Helton, R. L. Iman, D. E. Longsine, N. R. Ortiz, G. E. Runkle, and M. J. Shortencarier. 1987. *Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report*. NUREG/CR-2452, SAND81-2573. Albuquerque, NM: Sandia National Laboratories.

Freeze, R. A., and J. A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Guzowski, R. V. 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-7149. Albuquerque, NM: Sandia National Laboratories.

Hora, S. C., D. von Winterfeldt, and K. M. Trauth. 1991. *Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*. SAND90-3063. Albuquerque, NM: SAndia National Laboratories.

Hubbard, N., D. Livingston, L. Fukui, and G. L. McVay, eds. 1984. "Composition and Stratigraphic Distribution of Materials in the Lower San Andres Salt Unit." *Materials Research Symposia Proceedings, Boston, MA, November 14, 1983*. Volume 26. New York, NY: Elsevier Science Publishing Company, Inc.

Hunter, R. L. 1989. *Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-2546. Albuquerque, NM: Sandia National Laboratories.

Kaplan, M. F. 1982. *Archeological Data as a Basis for Repository Marker Design*. ONWI-354. Washington, DC: U.S. Department of Energy.

Lappin, A. R., R. L. Hunter, D. P. Garber, P. B. Davies, R. L. Beauheim, D. J. Borns, L. H. Brush, B. M. Butcher, T. Cauffman, M. S. Y. Chu, L. S. Gomez, R. V. Guzowski, H. J. Iuzzolino, V. Kelley, S. J. Lambert, M. G. Marietta, J. W. Mercer, E. J. Nowak, J. Pickens, R. P. Rechard, M. Reeves, K. L. Robinson, and M. D. Siegel. 1989. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; March 1989*. SAND89-0462. Albuquerque, NM: Sandia National Laboratories.

Laul, J. C., and M. R. Smith. 1988. *Disequilibrium Study of Natural Radionuclides of Uranium and Thorium Series in Cores and Briny Groundwaters from Palo Duro Basin, Texas*. PNL/SRP-5783. Richland, WA: Pacific Northwest Laboratory.

LaVenue, A. M., T. L. Cauffman, and J. F. Pickens. 1990. *Ground-Water Flow Modeling of the Culebra Dolomite: Volume 1--Model Calibration*. SAND89-7068. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., S. G. Bertram-Howery, D. R. Anderson, K. Brinster, G. Guzowski, H. Iuzzolino, and R. P. Rechard. 1989. *Performance Assessment*

Methodology Demonstration: Methodology Development for Purposes of Evaluating Compliance with EPA 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant. SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

Martz, H. F., and M. C. Bryson. 1982. *Predicting Low-Probability/High-Consequence Events.* LA-UR-82-1668. Los Alamos, NM: Los Alamos National Laboratory.

Neretnieks, I., and A. Rasmussen. 1984. "An Approach to Modeling Radionuclide Migration in a Medium with Strongly Varying Velocity and Block Sizes along the Flow Path." *Water Resources Research* vol. 20, no. 12: 1823-1836.

Nowak, E. J., J. R. Tillerson, and T. M. Torres. 1990. *Initial Reference Seal System Design: Waste Isolation Pilot Plant.* SAND90-0355. Albuquerque, NM: Sandia National Laboratories.

Powers, D. W., S. J. Lambert, S-E Shaffer, L. R. Hill, and W. D. Weart, eds. 1978. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* 2 volumes. SAND78-1596. Albuquerque, NM: Sandia National Laboratories.

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.

Reeves, M., et al. 1991. *Regional Double-Porosity Solute Transport in the Culebra Dolomite Under Brine-Reservoir-Breach Release Conditions: An Analysis of Parameter Sensitivity and Importance.* SAND89-7069. Albuquerque, NM: Sandia National Laboratories.

Stormont, J. C., E. W. Peterson, and P. L. Lagus. 1987. *Summary of and Observations about WIPP Facility Horizon Flow Measurements through 1986.* SAND87-0176. Albuquerque, NM: Sandia National Laboratories.

Thomas, R. E. 1982. *Uncertainty Analysis.* ONWI-380. Washington, DC: Office of Nuclear Waste Isolation, U.S. Department of Energy.

Tierney, M. S. 1990. *Constructing Probability Distributions of Uncertain Variables in Models of the Performance of the Waste Isolation Pilot Plant.* SAND90-2510. Albuquerque, NM: Sandia National Laboratories.

U.S. DOE (Department of Energy). 1981. *Brine Pocket Occurrences in the Castile Formation, Southeastern New Mexico.* DOE/TME-3080.

U.S. DOE (Department of Energy). 1983. *Brine Reservoirs in the Castile Forrmation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico.* DOE/TME-3153.

U.S. DOE (Department of Energy). 1987. *Integrated Data Base for 1987: Spent Fuel and Radioactive Waste Inventories, Projects and Characterizations.* DOE/RW-0006, Rev. 3.

U.S. DOE (Department of Energy). 1989. *Radionuclide Source Term for the WIPP*. DOE/WIPP-88-005. Carlsbad, NM: U.S. Department of Energy.

U.S. DOE (Department of Energy). 1990a. *Integrated Data Base for 1990: Spent Fuel and Radioactive Waste Inventories, Projects and Characterizations*. DOE/RW-0006, Rev. 6.

U.S. DOE (Department of Energy). 1990b. *Final Supplement Environmental Impact Statement, Waste Isolation Pilot Plant*. DOE/EIS-0026-FS. Washington, DC: U.S. Department of Energy, Office of Environmental Restoration and Waste Management.

WIPP PERFORMANCE ASSESSMENT BIBLIOGRAPHY

PUBLISHED

Anderson, D. R., M. G. Marietta, and S. G. Bertram-Howery. 1991. *WIPP Performance Assessment: A 1990 Snapshot of Compliance with 40 CFR 191, Subpart B*. SAND90-2338. Albuquerque, NM: Sandia National Laboratories.

Anderson, D. R., M. G. Marietta, and S. G. Bertram-Howery. 1991. "WIPP Performance Assessment: A 1990 Snapshot of Compliance with 40 CFR 191, Subpart B." *Proceedings of the Probabilistic Safety Assessment and Management (PSAM) Conference, Beverly Hills, California, February 4-7, 1991.* Amsterdam: Elsevier Science Publishers. 893-898.

Bertram-Howery, S. G., and R. L. Hunter. 1989. *Plans for Evaluation of the Waste Isolation Pilot Plant's Compliance with EPA Standards for Radioactive Waste Management and Disposal*. SAND88-2871. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and R. L. Hunter, eds. 1989. *Preliminary Plan for Disposal-System Characterization and Long-Term Performance Evaluation of the Waste Isolation Pilot Plant*. SAND89-0178. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and P. N. Swift. 1990. *Status Report: Potential for Long-Term Isolation by the Waste Isolation Pilot Plant Disposal System.* SAND90-0616. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and P. N. Swift. 1991. *Early-1990 Status of Performance Assessment for the Waste Isolation Pilot Plant Disposal System.* SAND90-2095. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., and P. N. Swift. 1991. "Early-1990 Status of Performance Assessment for the Waste Isolation Pilot Plant Disposal System." *Proceedings of the Probabilistic Safety Assessment and Management (PSAM) Conference, Beverly Hills, California, February 4-7, 1991.* Amsterdam: Elsevier Science Publishers. 325-330.

Bertram-Howery, S. G., M. G. Marietta, D. R. Anderson, K. F. Brinster, L. S. Gomez, R. V. Guzowski, and R. P. Rechard. 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. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S. G., M. G. Marietta, R. P. Rechard, P. N. Swift, D. R. Anderson, B. L. Baker, J. E. Bean, Jr., W. Beyeler, K. F. Brinster, R. V. Guzowski, J. C. Helton, R. D. McCurley, D. K. Rudeen, J. D. Schreiber, and P. Vaughn. 1990. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990*. SAND90-2347. Albuquerque, NM: Sandia National Laboratories.

Brinster, K. F. 1991. *Preliminary Geohydrologic Conceptual Model of the Los Medaños Region near the Waste Isolation Pilot Plant for the Purpose of Performance Assessment*. SAND89-7147. Albuquerque, NM: Sandia National Laboratories.

Guzowski, R. V. 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-7149. Albuquerque, NM: Sandia National Laboratories.

Guzowski, R. V. 1991. *Evaluation of Applicability of Probability Techniques to Determining the Probability of Occurrence of Potentially Disruptive Intrusive Events at the Waste Isolation Pilot Plant*. SAND90-7100. Albuquerque, NM: Sandia National Laboratories.

Guzowski, R. V. 1991. *Preliminary Identification of Scenarios for the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND90-7090. Albuquerque, NM: Sandia National Laboratories.

Guzowski, R. V. 1991. "Preliminary Identification of Scenarios for the Waste Isolation Pilot Plant, Southeastern New Mexico." *Proceedings of the Probabilistic Safety and Management (PSAM) Conference, Beverly Hills, California, February 4-7, 1991*. Amsterdam: Elsevier Science Publishers. 337-342.

Guzowski, R. V., and M. M. Gruebel, eds. 1991. *Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*. SAND91-0928. Albuquerque, NM: Sandia National Laboratories.

Helton, J. C., J. W. Garner, R. D. McCurley, and D. K. Rudeen. 1991. *Sensitivity Analysis Techniques and Results for Performance Assessment at the Waste Isolation Pilot Plant*. SAND90-7103. Albuquerque, NM: Sandia National Laboratories.

Hora, S. C., D. von Winterfeldt, and K. M. Trauth. 1991. *Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*. SAND90-3063. Albuquerque, NM: Sandia National Laboratories.

Hunter, R. L. 1989. *Events and Processes for Constructing Scenarios for the Release of Transuranic Waste from the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-2546. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., S. G. Bertram-Howery, D. R. Anderson, K. F. Brinster, R. V. Guzowski, H. J. Iuzzolino, and R. P. Rechard. 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. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., S. G. Bertram-Howery, R. P. Rechard, and D. R. Anderson. 1991. "Status of WIPP Compliance with EPA 40 CFR 191, December 1990." *Proceedings of the 1991 International High-Level Radioactive Waste Management Conference - Public Safety and Technical Achievement, Las Vegas, Nevada, April 28-May 3,1991.*

Rechard, R. P. 1989. *Review and Discussion of Code Linkage and Data Flow in Nuclear Waste Compliance Assessments.* SAND87-2833. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P. 1991. *CAMCON: Computer System for Assessing Regulatory Compliance of the Waste Isolation Pilot Plant.* SAND90-2094. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P. 1991. "CAMCON: Computer System for Assessing Regulatory Compliance of the Waste Isolation Pilot Plant." *Proceedings of the Probabilistic Safety and Management (PSAM) Conference, Beverly Hills, California, February 4-7, 1991.* Amsterdam: Elsevier Science Publishers. 899-904.

Rechard, R. P. 1991. "Use of Risk to Resolve Conflicts in Assessing Hazards." *Proceedings of the First International Mixed-Waste Symposium, Baltimore, Maryland, August 26-29, 1991.*

Rechard, R. P., H. J. Iuzzolino, J. S. Rath, R. D. McCurley, and D. K. Rudeen. 1989. *User's Manual for CAMCON: Compliance Assessment Methodology Controller.* SAND88-1496. Albuquerque, NM: Sandia National Laboratories.

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.

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 Waste Isolation Pilot Plant Repository/Shaft System.* SAND89-2030. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., P. J. Roache, R. L. Blaine, A. P. Gilkey, and D. K. Rudeen. 1991. *Quality Assurance Procedures for Computer Software Supporting Performance Assessments of the Waste Isolation Pilot Plant.* SAND90-1240. Albuquerque, NM: Sandia National Laboratories.

Roache, P. J., P. M. Knupp, S. Steinberg, and R. L. Blaine. 1990. "Experience with Benchmark Test Cases for Groundwater Flow" in *FED-Vol. 93, Benchmark Test Cases for Computational Fluid Dynamics.* Eds. I. Celik and C. J. Freitas. American Society of Mechanical Engineers.

SNL (Sandia National Laboratories) WIPP Performance Assessment Division. 1991. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991—Volume 1: Methodology and Results.* SAND91-0893/1. Albuquerque NM: Sandia National Laboratories.

SNL (Sandia National Laboratories) WIPP Performance Assessment Division. 1991. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991—Volume 2: Probability and Consequence Modeling*. SAND91-0893/2. Albuquerque, NM: Sandia National Laboratories.

SNL (Sandia National Laboratories) WIPP Performance Assessment Division. 1991. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991—Volume 3: Reference Data*. R. P. Rechard, A. C. Peterson, J. D. Schreiber, H. J. Iuzzolino, M. S. Tierney, and J. S. Sandha, eds. SAND91-0893/3. Albuquerque, NM: Sandia National Laboratories.

Tierney, M. S. 1990. *Constructing Probability Distributions of Uncertain Variables in the Models of the Performance of the Waste Isolation Pilot Plant*. SAND90-2510. Albuquerque, NM: Sandia National Laboratories.

Tierney, M. S. 1991. *Combining Scenarios in a Calculation of the Overall Probability Distribution of Cumulative Releases of Radioactivity from the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND90-0838. Albuquerque, NM: Sandia National Laboratories.

Trauth, K. M., S. C. Hora, and R. P. Rechard. 1991. "Expert Judgment as Input to Waste Isolation Pilot Plant Performance-Assessment Calculations, Probability Distributions of Significant System Parameters." *Proceedings of the First International Mixed-Waste Symposium, Baltimore, Maryland, August 26-29, 1991*.

IN PREPARATION

Berglund, J., and M. G. Marietta. *A Computational Model for the Direct Removal of Repository Material by Drilling*. SAND90-2977. Albuquerque, NM: Sandia National Laboratories.

Blaine, T., and D. Jackson. *Environmental Pathways Data Base for WIPP Radiological Safety Assessments*. SAND90-7101. Albuquerque, NM: Sandia National Laboratories.

Gilkey, A. *ALGEBRA User's Manual*. SAND88-1431. Albuquerque, NM: Sandia National Laboratories.

Gilkey, A. *BLOT User's Manual*. SAND88-1432. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., D. R. Anderson, D. Scott, and P. N. Swift. *Review of Parameter Sensitivity Studies for the Waste Isolation Pilot Plant*. SAND89-2028. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., R. P. Rechard, P. N. Swift, and others. *Preliminary Probabilistic Safety Assessment of the Waste Isolation Pilot Plant*. SAND90-2718. Albuquerque, NM: Sandia National Laboratories.

Marietta, M. G., S. G. Bertram-Howery, R. P. Rechard, and D. R. Anderson. *Status of WIPP Compliance with EPA 40 CFR 191, December 1990*. SAND90-2424. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P. *CAMCON Architectural Overview and Program Reference Manual*. SAND90-1984. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., A. P. Gilkey, D. K. Rudeen, J. S. Rath, W. Beyeler, R. Blaine, H. J. Iuzzolino, and R. D. McCurley. *User's Reference Manual for CAMCON: Compliance Assessment Methodology Controller Version 3.0*. SAND90-1983. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., H. J. Iuzzolino, and J. S. Sandha. *Quality Assurance Procedures for Data Supporting Performance Assessments of the Waste Isolation Pilot Plant*. SAND91-0429. Albuquerque, NM: Sandia National Laboratories.

Rechard, R. P., P. J. Roache, J. W. Berglund, D. K. Rudeen, J. E. Bean, and J. D. Schreiber. *Quality Assurance Procedures for Analyses Supporting Performance Assessments of the Waste Isolation Pilot Plant*. SAND91-0428. Albuquerque, NM: Sandia National Laboratories.

Roache, P. J., R. Blaine, and B. L. Baker. *SECO 2.1 User's Manual*. SAND90-7096. Albuquerque, NM: Sandia National Laboratories.

SNL (Sandia National Laboratories) WIPP Performance Assessment Division. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991—Volume 4: Uncertainty and Sensitivity Analyses*. SAND91-0893/4. Albuquerque, NM: Sandia National Laboratories.

Swift, P. N., B. L. Baker, K. F. Brinster, M. G. Marietta, and P. J. Roache. *Parameter and Boundary Conditions Sensitivity Studies Related to Climate Variability and Scenario Screening for the Waste Isolation Pilot Plant*. SAND89-2029. Albuquerque, NM: Sandia National Laboratories.

GLOSSARY

absorption - The attraction of molecules of gases or ions in solution to the surface of solids in contact with them.

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 numbers 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.

alpha particle - A positively charged particle emitted in the radioactive decay of certain nuclides. Made up of two protons and two neutrons bound together, it is identical to the nucleus of a helium atom. It is the least penetrating of the three common types of radiation--alpha, beta, and gamma.

alternative conceptual model - Multiple working hypotheses of a system. Part of a formalized procedure of inquiry first proposed by T. C. Chamberlin in 1890. The purpose is to "divide our affection, suggest critical tests, and expose more facets of a system," thereby avoiding being too strongly swayed by one conceptual model (set of hypotheses) and unwittingly seeking only facts to support it.

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 concave downward (convex upward), whose core contains stratigraphically older rocks.

aperture - The open space caused by 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 less permeable unit in a hydrostratigraphic sequence that retards but does not prevent the flow of water to or from an adjacent aquifer.

argillaceous - Containing clay-sized particles or clay minerals.

argillic - See argillaceous.

backfill - Material filling a former excavation (e.g., salt placed around the waste containers, filling the open space in the room).

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])*

benchmark - To compare model predictions made with one applied model with those obtained with other implementations of analytic or numerical computational models. Benchmarking is a part of verification.

bentonite - A commercial term applied to expansive clay materials containing montmorillonite (smectite) as the essential mineral.

beta distribution - A useful model for random variates defined on a finite interval. The beta distribution permits representation of a wide variety of distributional shapes by selection of two shape parameters.

biodegradable - Capable of being broken down by microorganisms.

biogenic - Produced directly by the physiological activities of organisms, either plant or animal.

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).

biotransformation - The changing of chemical compounds within a living system.

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 aquifer moves upward dissolving more soluble rocks 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 - See brine reservoir.

brine pocket - See brine occurrence.

brine reservoir - Pressurized brine in the Castile Formation; also referred to as "brine pocket" or "brine occurrence."

calibrate - To vary parameters of an applied model within reasonable range until differences between observed data and computed values are minimized (subjective).

canister - For the WIPP, it is a container, usually cylindrical, for remotely handled waste, spent fuel, or high-level waste; affords physical containment during handling but not radiation shielding.

capacitance - In hydrology, the combined compressibility of the solid porous matrix and the fluid within the pores.

capture volume - The maximum volume of waste through which neutrally buoyant particles can pass (by means of being carried along with brine) within a given time period (usually 10,000 years).

cask - A shipping container that is radiation shielded.

cationic - Pertaining to positively charged ions.

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) correlated variables from 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 computational model is the implementation of the mathematical model. The implementation may be through analytic or numerical solution. Often the analytic solution is numerically evaluated (e.g., numerical integration or evaluation of complex functions); hence, both solution techniques are typically coded on the computer. Consequently, the computational model is often called a computer model.

computer model - The appropriately coded analytical, quasi-analytical, or numerical solution technique used to solve a mathematical model; generic, until site-specific data are used.

conceptual model - The set of hypotheses (preferably based on observed data) that postulate the description and behavior of the disposal system (e.g., structural geometry, material properties, and significant physical processes that affect behavior). For WIPP, the data pertinent for a conceptual model are stored in the secondary data base.

conductivity - A shortened form of hydraulic conductivity.

confined groundwater - Groundwater occurring in an aquifer bounded above and below by an aquitard.

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.

connectivity - The manner in which individual nodes or points connect together to form elements or legs.

consequence module - A module of the CAMCON system that assesses the consequences of radionuclides being transported from the repository.

consolidate - To cause loosely aggregated, soft, or liquid earth materials to become firm and coherent.

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.

criticality - The state of a mass of fissionable material when it is sustaining a chain reaction.

cumulative distribution function - The sum (or integral as appropriate) of the probability of those values of a random variable 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 flow - Pertaining to a formula derived by Darcy for the flow of fluids through porous media, which states that flow is directly proportional to the hydraulic gradient, the cross-sectional area through which flow occurs, and the hydraulic conductivity.

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.

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.

diffusion - The transfer of mass 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 disposal region, shafts, and controlled area.

disturbed rock zone - That portion of the geologic barrier of which the physical or chemical properties may have changed significantly as a result of underground construction.

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 - Characterized by or tending to produce continuous change or advance.

empirical - Relying explicitly upon or derived explicitly from observation or experiment.

emplacement - At WIPP, the placing of radioactive wastes within the waste rooms.

equipotential - Points with the same hydraulic head.

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.

evapotranspiration - Loss of water from a land area through transpiration of plants and evaporation from the soil.

event - A phenomenon 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.

exponential distribution - A probability distribution whose pdf is an exponential function defined on the range of the variable in question.

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.

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.

frequentist - One who believes that the probability of an event is the ratio of the number of times the event occurs in a series of trials of a chance experiment to the number of trials performed.

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.

gradational - Gradual change in rock characteristics from one rock body to another.

grout - A cement slurry of high water content.

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.

headward erosion - The lengthening and cutting upstream of a young valley or gully above the original source of its stream.

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 - Of, involving, moved, or operated by a fluid under pressure.

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 above a datum to which water would rise at a given point in a well open to an aquifer. It is a function of the elevation of the aquifer and the fluid pressure within it.

hydrochemical - The diagnostic chemical character of ground water occurring in hydrologic systems.

hydrodynamic dispersion - The tendency of a solute to spread out from the path that it would be expected to follow according to the advective hydraulics of the solvent.

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 water wells closely spaced for testing on hydrostratigraphic units.

hydrophobic - Lacking an affinity for, repelling, or failing to adsorb or absorb water.

hydrostatic - Pressure caused by the weight of overlying fluid.

hydrostratigraphic - Pertaining to a body of rock in which lateral variations in hydraulic properties within the study area are less significant than vertical variations between it and the overlying and underlying units.

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.

intergranular - Between the grains or particles of a rock.

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 thickness of a designated stratigraphic unit or group of stratigraphic units.

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 - Having the same property in all directions.

iterative - A computational procedure in which repetition of a set of operations produces results that approximate the desired result more and more closely as the number of repetitions increases.

jointing - The condition or presence of parallel fractures or partings in a rock, without displacement.

karst - A topography formed from solution of limestone, dolomite, or gypsum; characterized by sinkholes, caves, and underground drainage.

karstification - The formation of karst features by the solutional and mechanical action of water.

kriging - Geostatistical method for estimating magnitude plus uncertainty of a quantity (e.g., hydrogeological parameters), that is distributed in space and is measured in a network of points, at points other than the points of the network.

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.

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 cumulative distribution function 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.

ligands - Ions bound to a central atom in a compound.

limey - Containing calcium carbonate ($CaCO_3$).

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.

lognormal distribution - A probability distribution in which the logarithm of the variable in question follows a normal distribution.

loguniform distribution - A probability distribution in which the logarithm of the variable in question follows a uniform distribution.

low - A general geologic term for such features as a structural basin, a syncline, a saddle, or a sag.

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.

material attribute - Material characteristic that varies at each element of a mesh of a numerical model.

material property - Characteristic of the material that remains constant throughout the mesh of a numerical model.

mathematical model - The mathematical representation of a conceptual model (e.g., as coupled algebraic, differential, or integral equations with proper boundary conditions that approximate the physical processess in a specified domain of the conceptual model).

mean - The expectation of a random variable; i.e., the sum (or integral) of the product of the variable and the pdf over the range of the variable.

median - That value of a random variable at which its cdf takes the value 0.5; i.e., the 50th percentile point.

mesh - A subdivision of the domain of some mathematical model into cells for purposes of numerical solution.

microbiology - A branch of biology dealing especially with microscopic forms of life.

microcrystalline - Crystals too small to see with the naked eye.

microfracturing - The formation of fractures that cannot be detected with the unaided eye.

microwave - Electromagnetic radiation having wavelengths between 100 centimeters and 1 millimeter.

mode - That value of a random variable at which its pdf takes its maximum value.

modeler - One who studies a phenomenon or system by making a model of that phenomenon or system.

modular - Constructed with standardized units or dimensions for flexibility and variety in use.

module - A standardized computer program within a functional aggregation of computer programs.

molal - Concentration of a solution expressed in moles of solute per 1000 grams of solvent.

monocline - A local steepening in an otherwise uniformly gentle dip.

Monte Carlo sampling - A random sampling technique used in computer simulation to obtain approximate solutions to mathematical or physical problems.

mud - In drilling, a carefully formulated 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 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.

neoprene - A synthetic rubber made by the polymerization of chloroprene.

neutron - An elementary particle that has approximately the same mass as the proton but lacks electric charge, and is a constituent of all nuclei having mass number greater than 1.

Newtonian fluid - Pertaining to a substance in which the rate of shear strain is directly proportional to the shear stress.

noncombustibles - Materials that will not burn.

normal (or Gaussian) distribution - A probability distribution in which the pdf is a symmetric, bell-shaped curve of bounded amplitude extending from minus infinity to plus infinity.

nuclide - A species of atom characterized by the construction of its nucleus.

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.

overgrowth - Secondary material deposited around a crystal grain of the same composition.

overpack (waste) - A container put around another container. In the WIPP, overpacks would be used on those damaged or otherwise non-transportable 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 ($FeO \cdot OH \cdot nH_2O$).

paleoclimate - A climate of the geologic past.

paleosol - A buried soil horizon 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])*

perched groundwater - Groundwater occurring in a discontinuous saturated zone and separated from an underlying body of groundwater by an unsaturated zone. Its water table is a perched water table.

performance assessment - Performance assessment is defined by Subpart B of *40 CFR 191* 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.

physico-chemical - Pertaining to physical chemistry.

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.

plankton - Aquatic organisms that float passively or exhibit limited locomotor activity.

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.

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: $K_2MgCa_2(SO_4)_4 \cdot 2H_2O$; 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 - In physics, the work required to bring a unit electrical charge, magnetic pole, or mass from an infinitely distant position to a designated point in a static electrical, magnetic, or gravitational field, respectively.

potentiometric surface - An imaginary surface representing the head of groundwater and defined by the level to which water will rise in a well.

predictive - Foretelling or predicting something; for the WIPP, predicting future states of the repository system.

probabilistic - Using or pertaining to probabilities or probability theory.

probability density function - For a continuous random variable X, the function giving the probability that X lies in the interval x to x+dx centered about a specified value x (i.e., the derivative of the cumulative distribution function).

process - A phenomenon that occurs over a significant portion of the time frame of interest.

quality assurance - All those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

rad - A basic unit of absorbed dose defined as an energy absorption of 100 erg/g by a specified material from any ionizing radiation incident upon that material.

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.

radiochemistry - The chemical study of irradiated and naturally occurring radioactive materials and their behavior.

radiological - Pertaining to 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.

recrystallization - The formation, essentially in the solid state, of new crystalline mineral grains in a rock. The new grains are generally larger than the original grains and may have the same or a different mineralogical composition.

reentrant - A prominent, generally angular indentation in a land form.

rem - Roentgen equivalent in 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 unity, 1 rem is equal to 1 rad.

repository - The portion of the WIPP facility 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 speed divided by mean speed.

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 general representation of risk is a set $R = \{(S_i, pS_i, cS_i), i = 1, \ldots, nS\}$ 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.

saturated - All connected pores in a given volume of material 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 cause or promote the escape of radionuclides from the repository.

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.

semilog - Graph or chart having a logarithmic scale on one axis and an arithmetic scale or uniform spacing on the other axis.

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])*

silicification - The introduction of, or replacement by, silica, generally resulting in the formation of fine-grained quartz, which may fill pores and replace existing minerals.

siliclastic - Clastic, noncarbonate rocks that contain almost exclusively quartz or other silicate minerals.

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 or funnel-shaped depression at the land surface generally caused by solution 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.

solubility - The equilibrium concentration of a solute when undissolved solute is in contact with the solvent.

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 could be mobilized for possible transport to the accessible environment, and the rates at which these radionuclides could 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.*

stationarity - A stochastic process is said to be stationary in time (or space) if its statistical properties are invariant under arbitrary time (or space) translations.

stochastic process - Any process occurring in space and/or time whose descriptive variables are random variables; synonymous with random function, random field, 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.

subjective - Proceeding from or taking place within an individual's mind (as opposed to empirical, i.e., supported by explicit records of measurements or experiments).

surfactant - A surficially 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.

syndepositional - Forming contemporaneously with deposition.

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.

thermodynamic - Pertaining to the relationship of heat to mechanical and other forms of energy.

tight - Pertaining to a rock that has all interstices filled with fine grains or with matrix material so that porosity and permeability are almost non-existent.

topography - The configuration of a land surface, including its relief and the position of its natural and man-made features.

tortuosity - A measure of the actual length of the path of flow through a porous medium.

transgressive - The spread or extension of the sea over land areas, and the consequent evidence of such an advance (such as strata deposited unconformably on older rocks).

transiency - The state or quality of being transient.

translator - A computer program that translates output from one program to input for another program. Also referred to as pre- and post-processors.

transmissivity - For a confined aquifer, the product of hydraulic conductivity and aquifer thickness.

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.

truncated distribution - A probability distribution defined on a range of variable values that is smaller than the range normally associated with the distribution: e.g., a normal distribution defined on a finite range of variable values.

turbidity current - A density current in water, air, or other fluid, caused by different amounts of matter in suspension; specifically a bottom-flowing current laden with suspended sediment moving swiftly (under the influence of gravity) down a subaqueous slope and spreading horizontally on the floor of a body of water.

unconfined - Used to describe an aquifer that is not bounded above and below by an aquitard.

unconformably - Not conformable, i.e., a break in deposition of sedimentary material.

unconformity - A substantial break or gap in the geologic record in which a rock unit is overlain by another that is not normally next in stratigraphic succession.

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 probability distribution in which the pdf is constant over the range of variable values.

unsaturated - Refers to a rock or soil in which the pores are not completely filled with a fluid (usually water, but also other liquids and gas).

Uranium-234/Uranium-238 activity ratio - Comparison of the radioactivities of U-234 and U-238; the change in this ratio in groundwater can be related to the passage of time because U-238 decays to the more soluble Th-234, which in turn decays to U-234. As a result, the ratio of U-234 to U-238 in groundwater increases with time.

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 of a model using real site data that a conceptual model and the corresponding mathematical and computer models correctly simulate a physical process with sufficient accuracy.

variable - Any quantity supplied as an ingredient of a model, or a computer program that implements a model; also referred to as a parameter.

variance - The square of the standard deviation; the variance is a measure of the amount of spreading of a probability density function about its mean.

verification - The process of assuring (e.g., through tests on ideal problems) that a computer code (computational model) correctly performs the stated capabilities (such as solving the mathematical model). Given that a computer code correctly solves the mathematical model, the physical assumptions of the mathematical model must then be checked through validation.

vug - A small cavity in a rock.

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.

NOMENCLATURE

Acronyms and Initialisms

AEC - Atomic Energy Commission

AKRIP - Computer program used for kriging

ALGEBRA - CAMDAT computer program that algebraically manipulates data and plots meshes and curves.

ASCII - American Standard Code for Information Exchange

BCSET - Computer program that sets up boundary conditions.

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.

BRAGFLO - Computer program that simulates two-phase flow (brine and gas) in a three-dimensional, porous medium.

BRWM - Board on Radioactive Waste Management of the National Research Council

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 - See Glossary: complementary cumulative distribution function

CCDFCALC - Computer program used to calculate a CCDF

CCDFPLT - Computer program that calculates and plots the complementary cumulative distribution function.

CCD2STEP - Computer program that translates from CCDFCALC.

cdf - See Glossary: cumulative distribution function

CFR - Code of Federal Regulations

CHAIN - Computer program that generates radionuclide chains.

CHANGES - Computer program that is a record of needed enhancements to CAMCON or codes.

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.

DISTRPLT - Computer program that plots a pdf's given parameters.

DOE - The U.S. Department Of Energy, established in 1978 as a successor to the Energy Research and Developmment Administration (ERDA).

DOSE - Computer program that calculates human doses from transfer factors.

DRZ - See Glossary: disturbed rock zone

DST - Drill-stem test

E1 - A scenario for the WIPP consisting of one or more boreholes that penetrate through a waste-filled room or drift and continue into or through a brine pocket in the underlying Castile Formation.

E2 - A scenario for the WIPP consisting of one or more boreholes that penetrate to or through a waste-filled room or drift in a panel but do not intersect brine or any other important source of water.

E1E2 - A scenario for the WIPP consisting of exactly two boreholes that penetrate waste-filled rooms or drifts in the same panel, with one borehole also penetrating a brine reservoir in the underlying Castile Formation.

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

FASTQ - Computer program that generates finite element meshes.

FD - Finite difference (numerical analysis)

FE - Finite element (numerical analysis)

FEIS - Final Environmental Impact Statement

50 FR 38066 - Federal Register, Volume 50, p. 38066

FITBND - Computer program that optimizes fit-of-pressure boundary conditions.

FLINT - Computer program that is a FORTRAN language analyzer.

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

GARFIELD - Computer program that generates attribute fields (e.g., transmissivity)

GENII - Computer program that calculates human doses.

GENMESH - Computer program that generates three-dimensional, finite difference, meshes.

GENNET - Computer program that generates networks.

GENOBS - Computer program that generates functional relationships between well heads and pressure boundary conditions.

GENPROP - Computer program for item entry into a property data base.

GRIDGEOS - Computer program that interpolates observational hydrologic or geologic data onto computational meshes.

GROPE - File reader for CAMDAT.

HEPA - 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

ICSET - Computer program that sets up initial conditions.

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.

LHS2STEP - Computer program that translates from LHS to STEPWISE or PCCSRC.

LISTDCL - Computer program that lists DEC command procedural files.

LISTFOR - Computer program that lists programs and subroutines and summarizes comments and active FORTRAN lines.

LISTSDB - Computer program that tabulates data in a secondary data base for reports.

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.

NEFDIS - Computer program that plots NEFTRAN discharge history as a function of time.

NEFTRAN - Network Flow and TRANsport. Computer program that calculates flow and transport along one-dimensional legs comprising a flow network.

NRC - Nuclear Regulatory Commission

NUCPLOT - Computer program for a box plot of each radionuclide contribution to a CCDF.

NWPA - Nuclear Waste Policy Act (Public Law 97-425 & 100-203)

PA - Performance Assessment

PANEL - Computer program for a panel model that estimates radionuclide flow to the Culebra Dolomite Member through one or more boreholes.

PATEXO - Computer program that transforms PATRAN to CAMDAT.

PCCSRC - Computer program that calculates partial correlation and standardized regression coefficients.

pdf - See Glossary: probability density function.

PLOTSDB - Computer program that plots parameter distribution in a secondary data base.

POSTBOAST - Post-processor computer program (translator) for BOAST_II.

POSTBRAGFLO - Post-processor computer program (translator) for BRAGFLO.

POSTHST - Post-processor computer program (translator) for HST3D.

POSTLHS - Post-processor computer program (translator) for LHS.

POSTNEF - Post-processor computer program (translator) for POSTNEF.

POSTSTAFF - Post-processor computer program (translator) for STAFF2D.

POSTSUTRA - Post-processor computer program (translator) for SUTRA.

POSTSWIFT - Post-processor computer program (translator) for SWIFTII.

PRA - Probabilistic risk assessment

PREBOAST - Pre-processor computer program (translator) for BOAST II.

PREBRAGFLO - Pre-processor computer program (translator) for BRAGFLO.

PREHST - Pre-processor computer program (translator) for HST3D.

PRELHS - Pre-processor computer program (translator) for LHS.

PRENEF - Pre-processor computer program (translator) for NEFTRAN.

PRESTAFF - Pre-processor computer program (translator) for STAFF2D.

PRESUTRA - Pre-processor computer program (translator) for SUTRA.

PRESWIFT - Pre-processor computer program (translator) for SWIFTII.

QA - See Glossary: 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)

RELATE - Computer program that interpolates from coarse to fine mesh and fine to coarse mesh (relates property and boundary conditions).

RESHAPE - Computer program that redefines blocks (i.e., groupings of mesh elements).

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.

SAR - Safety Analysis Report

SCANCAMDAT - Computer program that quickly summarizes the data in CAMDAT.

SCP - Site characterization plan

SECO_2DH - Computer program for horizontal, two-dimensional groundwater flow simulation.

SEIS - Supplement Environment Impact Statement

SNL - Sandia National Laboratories

SORTLHS - Computer program that reorders vectors for LHS (Latin hypercube sampling).

SRC - Standardized regression coefficients

STAFF2D - Computer program for a finite-element transport model.

STEPWISE - Computer program that performs stepwise regression including rank regression.

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.

SUTRAGAS - SUTRA computer program modified for fluid as a gas instead of as a liquid.

SWB - Standard waste box

SWIFTII - Sandia Waste-Isolation Flow and Transport computer program that simulates saturated flow and heat, brine, and radionuclide chain transport in porous and fractured media.

TRACKER - Computer program that tracks neutrally buoyant particles in a steady or transient flow.

TRU - TRansUranic

TS - An event considered in scenario development for the WIPP consisting of subsidence that results due to solution mining of potash.

TXT2CAM - Computer program for ASCII to binary CAMDAT conversion.

UNSWIFT - Computer translator program that converts SWIFTII input files into CAMDAT.

WAC - Waste Acceptance Criteria

WEC - Westinghouse Electric Corporation

WIPP - Waste Isolation Pilot Plant

YMP - Yucca Mountain Project

Abbreviations and Symbols

Am - americium

atm - atmosphere

Ba - barium

Ce - cerium

Cf - californium

Ci - curie

cm - centimeter

Cm - curium

Co - cobalt

Cs - cesium

Cu - copper

Eh - oxidation potential

Eu - europium

Fe - iron

ft - foot

g - gram

gal - gallon

in - inch

kg - kilogram

km - kilometer

ℓ - liter

lb - pound

m - meter

M - Molar (molarity): Concentration of a solution expressed as moles of solute per liter of solution.

mg/ℓ - milligrams per liter

mi - mile

μd - microdarcy

md - millidarcy

Mn - manganese

MPa - megapascal (10^6 Pa)

mrem - millirem (10^{-3} rem)

nCi - nanocurie

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

s - second

Sb - antimony

Si - silicon

Sm - samarium

Sr - strontium

Te - tellurium

Th - thorium

U - uranium

Y - yttrium

yr - year

§ - section of 40 CFR Part 191

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