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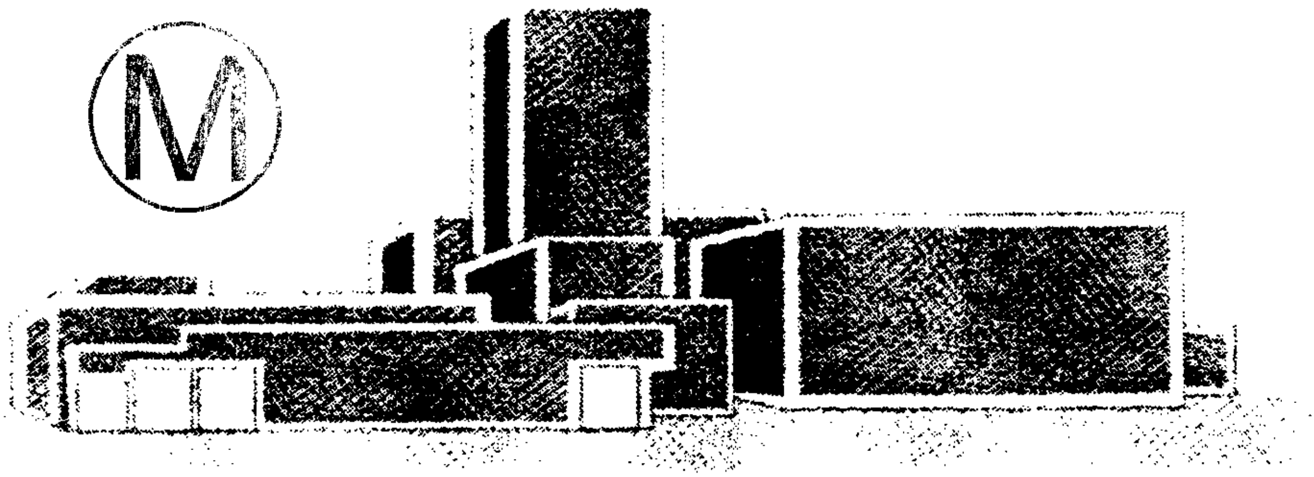
PEER 16 - Performance Assessment Review Team Peer Review

February 1994

PERFORMANCE ASSESSMENT REVIEW TEAM'S INDEPENDENT REVIEW OF WIPP PERFORMANCE ASSESSMENT ACTIVITIES

(40 CFR 191 AND 40 CFR 268.6)

FOR EM-342



APPENDIX A

GLOSSARY

REFERENCE LIST

Figure *Page*

Figure *Page*

EXECUTIVE SUMMARY

This report presents the findings of the Performance Assessment Review Team (PART), convened in 1992 to perform a limited, independent review of the Performance Assessment (PA) Program at the Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP). The six-member team was mandated by the Environmental Restoration and Waste Management WIPP Project Management Division (EM-342) of DOE to assess the adequacy of the WIPP PA program for meeting relevant regulatory standards for the disposal of radioactive and hazardous wastes, to identify any deficiencies in the program, and to make recommendations for improvements. In preparing its report, the PART reviewed the pertinent PA documents and activities, toured the WIPP site, and interviewed members of the project staff. The review team finds that the work on WIPP has generally been perceptive, incisive, and fundamentally sound. However, for compliance with current standards and regulations, substantial progress and improvements will be necessary in certain areas where additional investigations and documentation may be required; the PA department is fully aware of most of them. These areas include PA documentation, parameter evaluation, conceptual model justification, time-dependent behavior of natural and engineered barriers to fluid migration from the coupled disposal system, and a total system model.

The 10,250-acre WIPP site, located in the Permian age salt beds east of Carlsbad, New Mexico, was authorized by Congress (in Public Law 96-164) in 1979. The PART report begins with a history of the site selection and development and a summary of background information, focusing particularly on the facility's mission to investigate methods for the safe and permanent disposal of mixed transuranic (TRU) wastes in salt rock. Because of salt's impermeability, strength, and ability to "creep" and self-heal over time, waste emplaced in rooms mined from salt and backfilled and sealed with crushed salt will eventually be encapsulated and become part of the stable rock formation. If approved, the current WIPP plan would provide for the emplacement of 6.2 million ft^3 of waste in storage areas laid out in eight panels, each consisting of seven rooms.

The ultimate decision to license WIPP as a permanent repository and allow it to proceed with full-scale operations will depend on the ability of the DOE demonstration that the site is likely to satisfy the requirements of the various Federal and state regulations and address concerns of the oversight bodies (e.g., the National Environmental Policy Act (NEPA), the Resource Conservation and Recovery Act (RCRA), and the State of New Mexico's Environmental Evaluation Group {EEG}). In particular, the PART focused on the WIPP PA activities which address the long-term criteria in two key regulations:

- *40 CFR 191*–This regulation details the Environmental Protection Agency's (EPA's) standards for the Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Waste. Disposal systems are required to provide "a reasonable expectation" of adherence to specified limits on cumulative releases to the accessible environment, dose to the public, and groundwater contamination for 10,000 years. 40 CFR 191 Subpart B further decrees the use of specific methods for the containment and isolation of wastes (e.g., multiple barriers, both natural and engineered) and an evaluation of the possibility of inadvertent human intrusion into the disposal site. Sandia National

Laboratories (SNL) has the primary responsibility for performing the PA regarding 40 CFR 191 at WIPP.

- *40 CFR 268.6*–This RCRA regulation states that facilities planning to emplace untreated hazardous waste must obtain a No-Migration Determination (NMD) by demonstrating "to a reasonable degree of certainty" that there will be no migration of wastes for "as long as the wastes remain hazardous" (interpreted in this instance as 10,000 years). In 1990, WIPP was granted a ten-year conditional NMD for the Test Phase, and it is part of the duty of Westinghouse Waste Isolation Division (WID), which has responsibility for PA activities pertaining to 40 CFR 268.6, to supply the required annual reports to the EPA.

Differences or conflicts between the two regulations were reconciled by DOE in the draft Regulatory Criteria Document (RCD) in 1992. This set of integrated criteria was used by PART as the basis for its review, which examines the PA approaches of SNL and WID in terms of such issues as scenario selection and evaluation, conceptual modeling, performance measures, sensitivity and uncertainty analyses, and probabilistic approaches.

PART finds that the current PA documentation provides neither the framework nor history required for demonstrating reasonable expectation of compliance. The WIPP PA issues need to be tracked and documented from the time they are identified through their evaluation and eventual resolution. Of particular importance is the need to clearly document conceptual models of the disposal system and its components including the underlying assumptions, supporting information and any unresolved issues and their importance. From a performance measure standpoint, simple bounding calculations would be useful for building confidence and understanding of complex system models. Combined, these efforts would eventually lead to a well-documented, complete system model that will more clearly demonstrate whether the WIPP site complies with applicable regulations.

A substantial portion of the PART report is devoted to a review of the investigations of the stratigraphy, hydrology, structural state and chemistry of the host rock formations and the likely interactions between the disposal system and its natural surroundings. Despite considerable work on a constitutive relation for WIPP salt creep, which still requires improved understanding of the transient component, the relation has not yet been incorporated into models of repository closure. The effects of brine inflow and gas generation on room closure and sealing are beginning to be considered realistically in coupled, three-phase flow models but these models are not yet fully developed. Apart from uncertainties in the far-field hydraulic properties of the Salado Formation, the nature and projected behavior of the disturbed rock zone (DRZ) surrounding the excavation have not been well-characterized. The DRZ provides the primary potential pathway through time for the migration of gas and brine from disposal rooms to the accessible environment. Therefore, the representation of the DRZ is crucial in system performance models.

In conjunction with the natural barrier system, engineered barriers are designed to minimize releases to the accessible environment. Engineered barriers include repository design features, shaft and panel seals and plugs, and backfill; these components have not yet been incorporated into system performance models. The PART found that while substantial progress is being made towards characterizing natural barriers, more work will be required on engineered barriers before compliance can be demonstrated.

The final section of the investigation addresses undisturbed and disturbed repository scenarios considered by the PA. The undisturbed or base-case scenario assumes only naturally-occurring events and processes and modeling shows that lateral brine and gas releases in 10,000 years are very limited, as are vertical releases if shaft seals behave as expected. Disturbed repository scenarios investigated focus on future disruption by exploratory drilling for resources and consider probabilities and consequences of both direct and indirect releases to the accessible environment. For all three summary scenarios modeled, including a physically unreasonable and conservative one, releases estimated are well below the EPA regulatory limit. However, for both undisturbed and disturbed scenarios, only 2-D simulations using incomplete system models have been carried out, again emphasizing the need for complete systems performance modeling. Sensitivity analyses based on component models will not necessarily identify the most important variables and parameters for reducing uncertainty about the performance of the entire system.

The review team concludes that, although WIPP's work is generally solid, the current PA does not provide enough information or documentation on the underlying assumptions, controversial issues, and evolution of understanding to provide the confidence on the part of regulators and the public to support licensing of the WIPP facility. In addition to making specific suggestions regarding technical issues and uncertainties still in need of investigation and resolution, the necessity for including engineered barriers in future PAs, and the relative merit of more and less complex modeling efforts, the PART emphasizes the overall need for an integrating PA process which clearly relates ongoing WIPP activities to compliance-based objectives.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) of the United States Department of Energy (DOE), located near Carlsbad, New Mexico (**Figure 1-1**), was created as a research and development facility to demonstrate the safe disposal of the transuranic (TRU) wastes generated by national defense programs. Performance assessment is a key element in the ongoing development and potential certification of the facility. This report contains the findings and conclusions of the Performance Assessment Review Team (PART), which was formed by the Environmental Restoration and Waste Management WIPP Project Management Division (EM-342) of DOE to perform an independent review of the WIPP Performance Assessment (PA) Program.

1.1 AN OVERVIEW OF "PART'S INDEPENDENT REVIEW OF WIPP PA ACTIVITIES FOR EM-342"

EM-342 has oversight responsibility for the entire WIPP Project, including performance assessment activities. The objectives of the PART review were to assess the adequacy of the WIPP PA Program for meeting regulatory requirements, to identify any deficiencies in the program, and to make recommendations for program improvement.

The PART performed a limited review of relevant PA activities and documents and conducted interviews and discussions with WIPP Project staff, including the WIPP Project Integration Office (WPIO), Westinghouse Waste Isolation Division (WID), and Sandia National Laboratories (SNL) Performance Assessment Department. The review included an examination of the conceptual models used to represent the significant processes associated with a repository system at WIPP, the parameters defining the components of these models, and the activities for characterizing the site and reducing uncertainty in the long-term performance of the repository system. The results of these activities are summarized in this report.

Section 1 provides background information about the selection of WIPP as a disposal site for TRU waste, the history of its development, an overview of the regulations that govern the disposal of radioactive and hazardous waste in geologic repositories, and a summary of the general content of the PART review. Section 2 provides an overview of the PA requirements specified in the two Federal regulations governing geologic disposal of radioactive and hazardous waste. Section 2 also discusses similarities and differences in the current approaches taken for demonstrating compliance with these regulations.

Information about the WIPP site and the repository disposal system are provided in Sections 3, 4, and 5. Section 3 describes some of the conceptual models of key features and processes associated with the WIPP site and disposal system, including those aspects that were present before the WIPP facility was constructed and those that may be important in the distant future (i.e., during the next 10,000 years). Section 4 provides hydrologic and geologic data about the host rock and the formations above and below the repository. Emphasis is given to undisturbed properties to provide the basis for describing perturbations that occur or may occur as a result of repository construction and waste disposal. The possible impact of these activities on the long-term performance of the disposal system is discussed in Section 5.

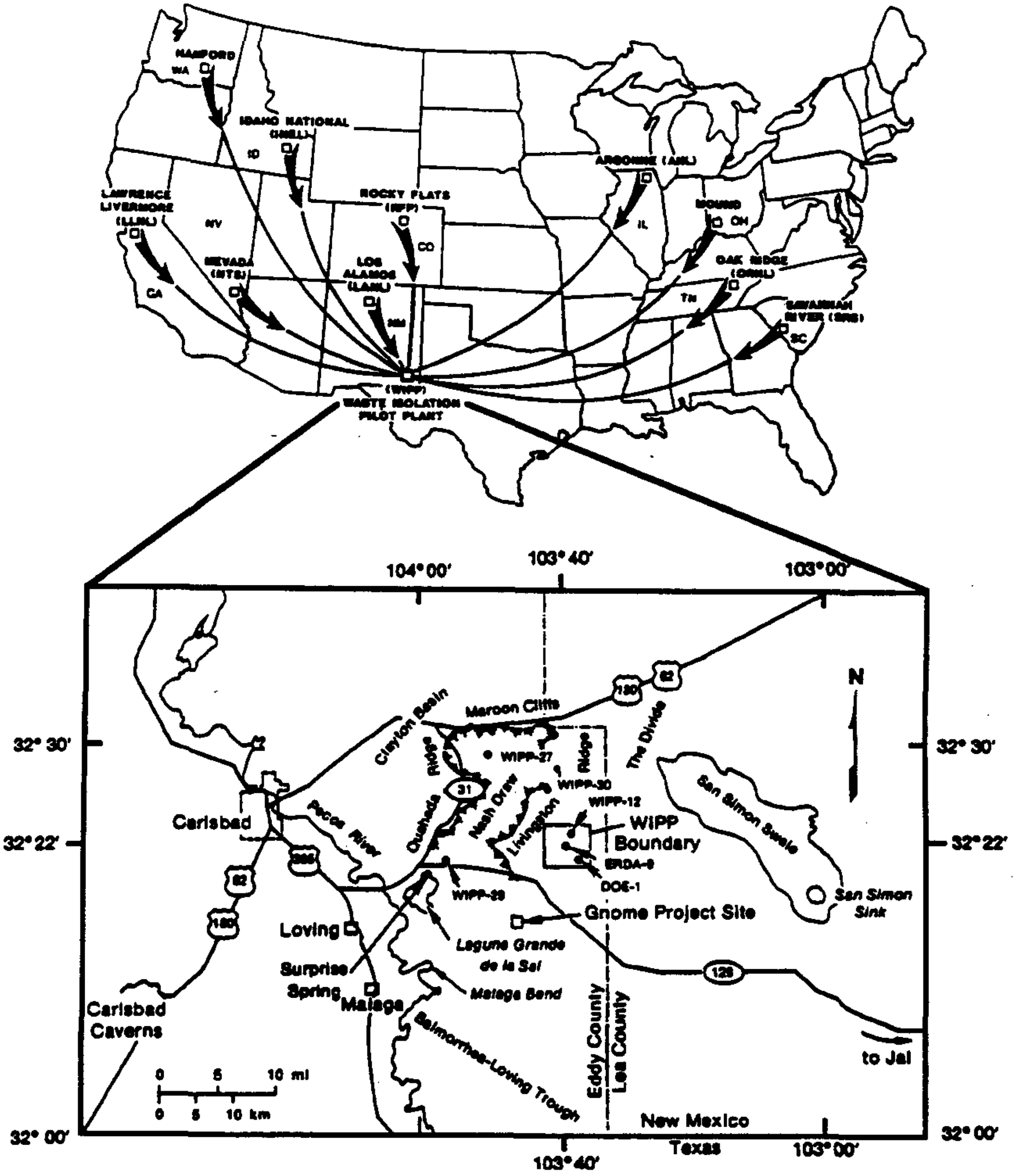


Figure 1-1. Location of WIPP in Southeastern New Mexico (after Rechard, 1989, Figure 1.2).

Section 6 contains an overview of the proposed engineered barrier system at WIPP, the associated standards in the regulations, and the relevant analyses and testing that have been performed. The section also identifies several issues concerning the treatment of the engineered barriers in the WIPP PA.

Scenarios of possible future events and processes at WIPP are presented in Section 7. The base case scenario for WIPP is presented in Subsection 7.1. This scenario ignores the possibility of human intrusion by mining or exploratory drilling and concentrates on expected changes in the natural system over the next 10,000 years. Inadvertent human intrusion scenarios are discussed in Subsection 7.2.

Section 8 discusses the major issues identified as part of the review that may affect the ability of DOE to demonstrate regulatory compliance. Observations are made concerning the difficulty of identifying all the sources of information relevant for the review and the reporting process, and recommended changes are provided. Areas of significant uncertainty and possible importance related to the natural and engineered components of the repository system are also discussed in Section 8. The significance of these findings cannot be assessed until a more comprehensive PA model is available.

1.2 BACKGROUND

This section provides background information on the WIPP project. It describes the history of its physical and regulatory development, as well as the nature and character of the wastes it is designed to handle. Numerous oversight and regulatory groups are also described in this section. Because the PART review examined the adequacy of the current PA program at WIPP for addressing the long term regulations, these regulations are described and their differences noted. The PART organization, the base set of information it used, the WIPP Project organizations that participated in the review, the meetings, the interviews and the tour that provided valuable inputs to PART, and the final report development are all described in this section.

Defense nuclear waste generation began in the 1940s. By the end of 1991, there were approximately 65,000 m^3 (2.3 million ft^3) of defense-related TRU wastes produced and/or temporarily stored at the various DOE facilities around the country (Figure 1-1). Projections indicate that by 2018 there will be 133,000 m^3 (4.7 million ft^3) of such wastes (DOE/RW-0006, Rev. 8, DOE/WIPP 89-011, Rev 1).

These wastes, containing less than 1% free liquids, consist of various items that must be discarded because they have become contaminated with long-lived radioactive elements like plutonium-239 (with a 24,000-year half-life), that are heavier than uranium (i.e., having an atomic number greater than 92). These items typically include rags, rubber gloves, shoe covers, discarded glass/metalware, plastic bags, pumps, motors, hand and machine tools, sludges and so forth. A significant portion of the TRU-contaminated waste, which can emit increasingly penetrating alpha, beta, and gamma radiation, also includes materials that are themselves designated as hazardous wastes by the Environmental Protection Agency (EPA)—e.g., volatile organic compounds (VOCs) such as carbon tetrachloride and metals such as lead (DOE/WIPP 89-011, Rev. 1).

Most TRU wastes (97%) are categorized as contact-handled (CH) TRU (less than 200 millirem/hr). Safe handling and storage are provided by packaging them in 55-gallon drums or boxes which will be stacked for disposal in the WIPP underground, as shown in **Figure 1-2**. The metallic drums or boxes provide sufficient shielding from the less penetrating alpha and beta radiation emitted by these wastes, and no additional shielding is required. The remaining small volume of TRU wastes (3%) is designated as remote-handled (RH) TRU waste. The RH TRU wastes emit sufficient quantities of gamma radiation (greater than 200 millirem/hr but less than 1000 rem/hr, with no more than 5% of the total greater than 100 rem/hr), and additional special shielding is required to protect workers and the public from radiation exposure during the transportation and emplacement of these wastes. Following a decision to store TRU wastes permanently at WIPP, TRU waste from the ten DOE facilities (Figure 1-1) that temporarily store and/or generate it, will be transported by truck to WIPP in NRC-certified Type B shipping containers (e.g., TRUPACT-II containers for CH-TRU, as illustrated in **Figure 1-3**).

The time sequence of events shown in **Figure 1-4** illustrates the complex intermingling of the events and periods of activity at WIPP with the times of passage of applicable public laws. Following the beginning of waste generation in the 1940's, the National Academy of Sciences (NAS) began investigating the feasibility of geological disposal of defense generated nuclear waste in the early 1950's. The NAS investigation resulted in the recommendation in 1957 (NAS-NRC 1957) of salt deposits as a promising medium for disposal of radioactive wastes for the following reasons:

- Salt is virtually impervious and has a natural "plastic-like" quality that enables it to flow or creep and self-heal over time under the effects of heat and stress found at proposed repository depths. As a result, waste emplaced in mined rooms within the salt deposits and backfilled with salt will eventually be encapsulated and become part of the stable rock formation .
- Circulating groundwaters are historically absent within salt formations (as shown by the existence of salt deposits), and the composition of inter- and intra-granular brines is consistent with connate water from the 225-million-year-old Permian Sea.
- Vast salt deposits are found in relatively stable geological areas with little earthquake activity.
- Salt is relatively easy to mine, and is as strong as ordinary concrete in the short term, but weak and ductile in the long-term.

Following the NAS recommendation, the United States Geological Survey (USGS) identified the salt beds of the Permian Basin of the southwestern U.S. (**Figure 1-5**) as a workable location for a repository in 1962. Subsequently, the Oak Ridge National Laboratory, following USGS recommendations, studied various potential repository locations in the Permian Basin and conducted extensive testing of sites in Kansas and New Mexico which included large-scale field experiments near Lyons, Kansas. The search ended and the WIPP site investigation period began in 1974, when a portion of the Northern Delaware Basin east of Carlsbad, New Mexico was chosen as the most promising location for a TRU waste repository.

In 1979, Public Law 96-164 established WIPP as a first-of-a-kind project to meet the national need for a long-term, safe method for disposal of TRU wastes from the nation's defense programs. WIPP's research and development mission was to study the characteristics of salt rock and how it interacts with, and can safely contain, TRU wastes; and to implement a three-to-seven-year production-scale test program to determine if TRU wastes can be safely disposed in a deep, underground, bedded salt formation.

Figure 1-2. Stacks of Drums at WIPP.

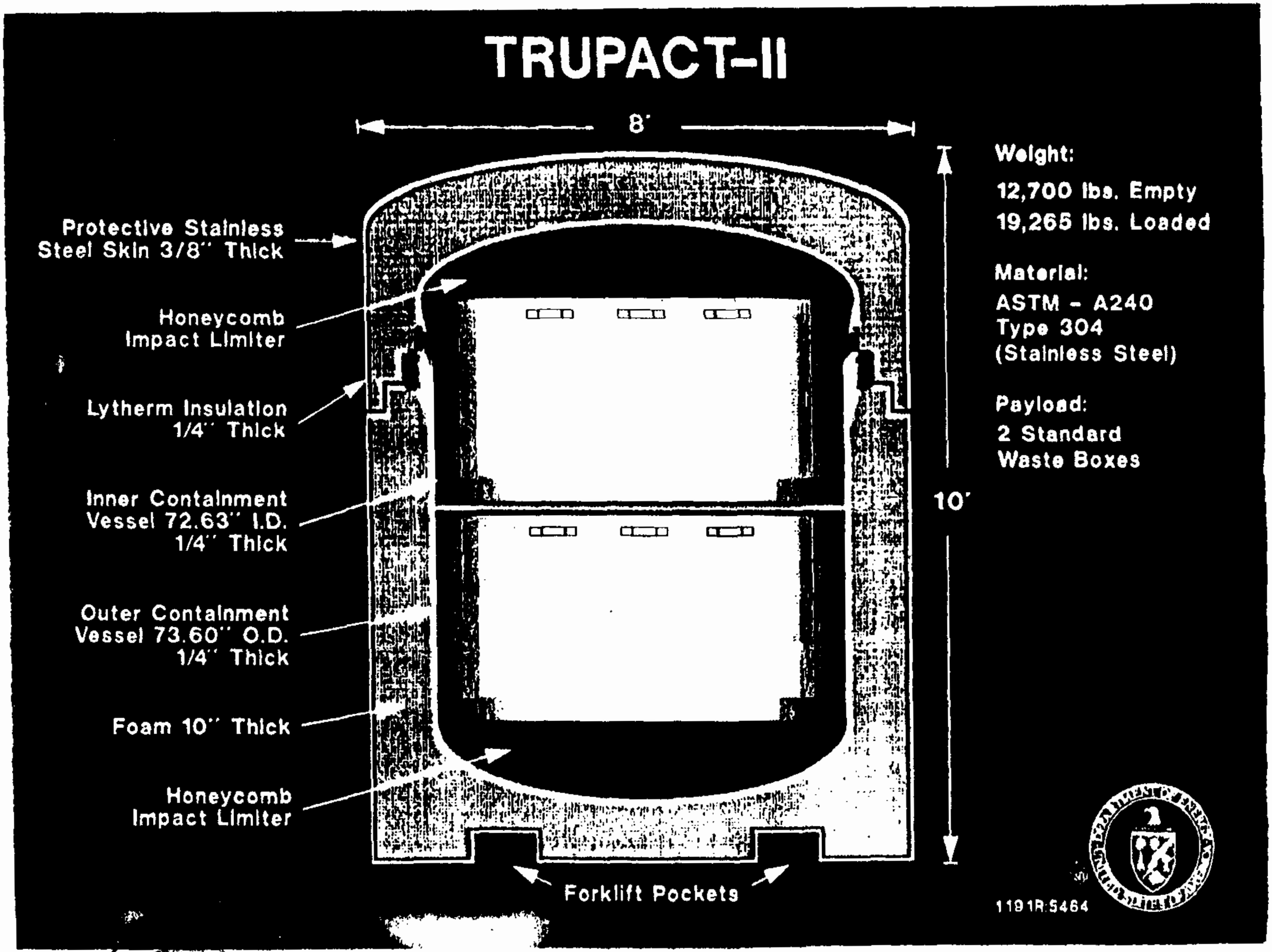


Figure 1-3. Diagram of the TRUPACT-II Double Containment Vessel for Transport of W[illegible] WIPP.

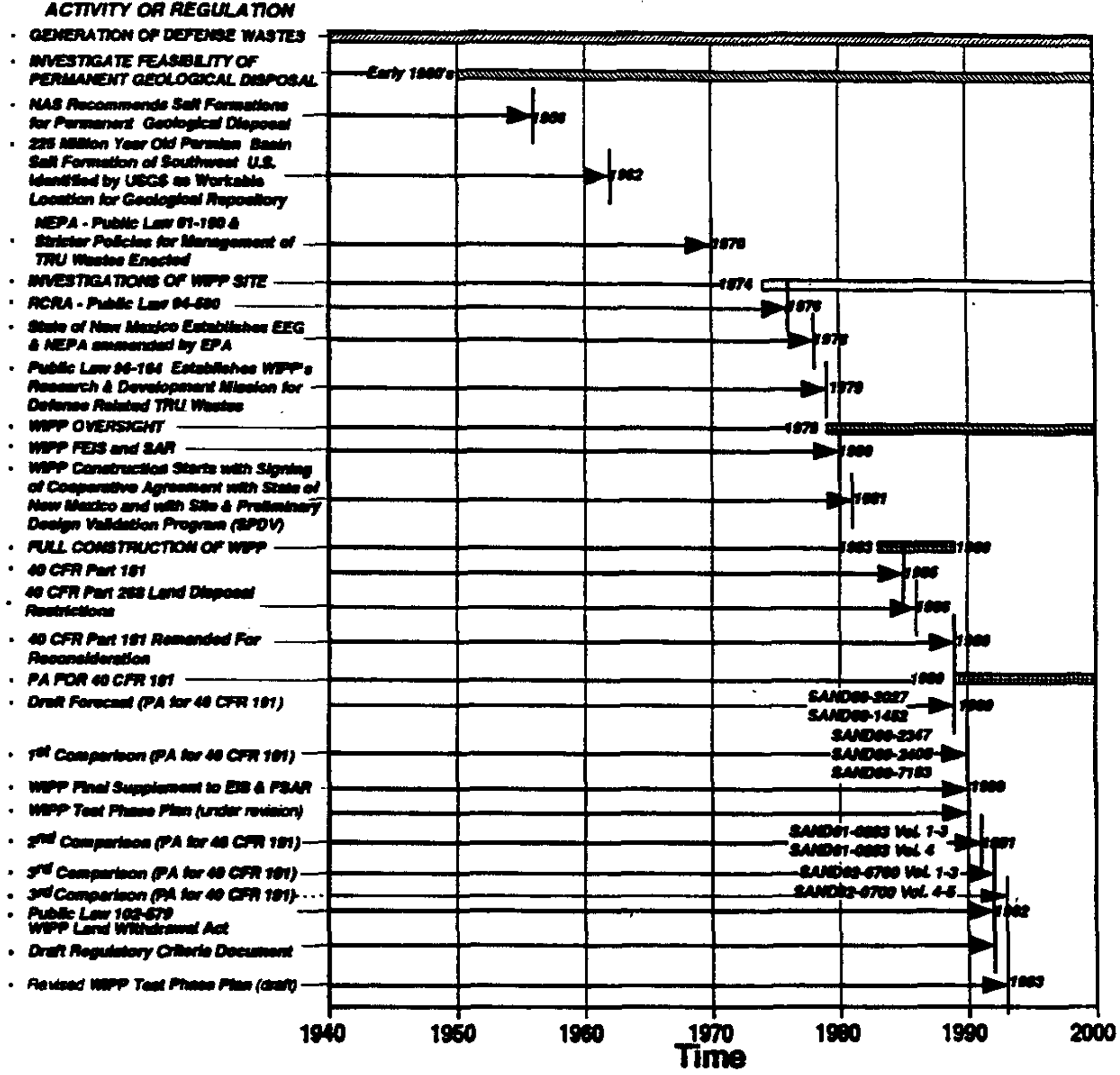


Figure 1-4. Timing of WIPP Events and Actions.

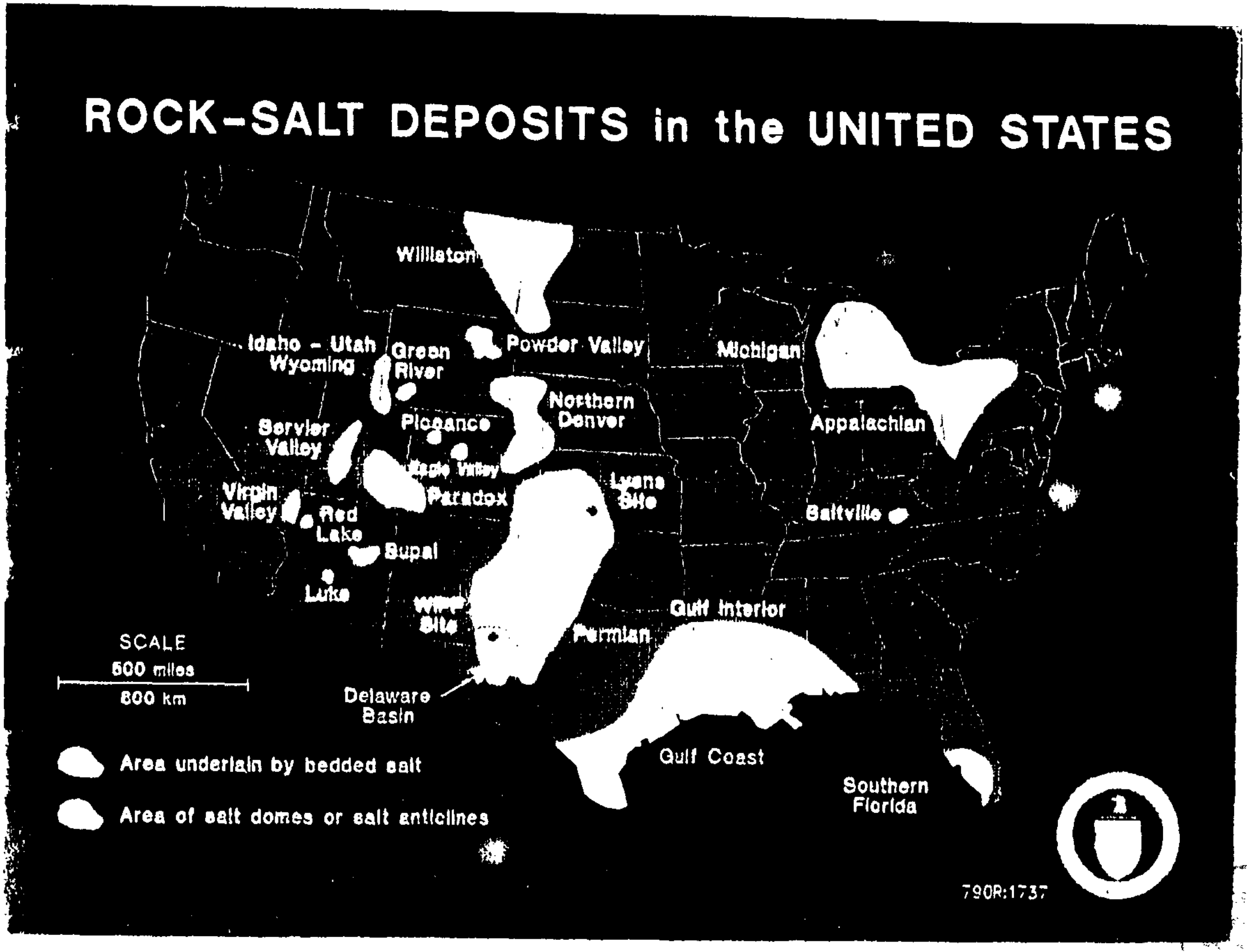


Figure 1-5. Location of Variou ck-Salt Deposits in the United States

If the tests prove successful, and a decision is made to store mixed TRU wastes permanently at WIPP, the facility will operate as a repository for approximately twenty years before closure.

Between the site selection period and 1979, when the WIPP site was authorized by Congress, important events occurred that impacted WIPP significantly. The National Environmental Policy Act (NEPA) became law, and stricter policies for the management of TRU wastes were enacted by Congress in 1970. The Resource Conservation and Recovery Act (RCRA) was enacted (1976), NEPA was amended (1978), and the Environmental Evaluation Group (EEG) was established to provide a comprehensive overview of soon-to-be-authorized WIPP Project activities.

1.2.1 Development and Construction of WIPP

Before construction of the facilities could begin, the following three reports were prepared to develop the facility design and establish technical adequacy:

- Final Environmental Impact Statement (FEIS), issued in 1980 to implement NEPA,
- Safety Analysis Report (SAR), also issued in 1980, and
- Site and Preliminary Design Validation (SPDV) report, initiated in 1981.

While construction started at WIPP in 1981 with the SPDV Program, full construction of all facilities did not begin until 1983; construction of surface facilities was completed in 1989.

Figure 1-6 illustrates a 1991 northwest-looking aerial view of the WIPP surface facilities, and **Figure 1-7** shows a northeast-looking isometric view of the layout of WIPP's surface and the underground footprint. The plan view diagram of the WIPP underground shown in **Figure 1-8** differentiates between completed and proposed excavations. As indicated in these figures, WIPP consists of both underground facilities and surface facilities that house site personnel and equipment for operational and research activities. Underground facilities include a series of horizontal storage rooms, alcoves, and tunnels, and four vertical shafts (i.e., salt handling, waste, exhaust, and air intake shafts). Figure 1-8 illustrates the basic dimensions of the underground workings and shows that they consist of a waste storage area and an active experimental area. Current design provides for emplacement of 175,564 m^3 (6.2 million ft^3) of TRU waste in storage areas to be laid out in ten panels. These ten panels include eight main panels and two equivalent panels to be developed in the access tunnels during the last stages of disposal (i.e., a northern and a southern panel), as illustrated in Figure 1-8. The main panels consist of seven rooms (dimensions 4.0 m high, 10.0 m wide, 91.4 m long {13 ft high, 33 ft wide, 300 ft long}) and the connecting passages. By 1990, approximately 16 km (10 mi) of underground structure had been excavated. This required the removal of 800,000 tons of rock salt or about 50% of the estimated 1.6 million tons to be removed if a decision to dispose is reached. In addition to the 16 km (10 linear mi) of tunnels more than 16 km (10 vertical mi) of drill holes have been completed to characterize the site.

Figure 1-9 shows the WIPP-area stratigraphic column and an idealized geologic profile illustrating the surface buildings and four shafts going down to the repository level 655 m (2,150 ft) below the surface. The underground facility is roughly centered in the sequence of evaporite deposits that make up the Salado Formation. The 914 m (3,000 ft) thick Permian-age salt beds at WIPP are some of the thickest in the United States. These 245- to 285-million-year-old Permian Basin salt deposits, which underlie a large portion of eastern New Mexico, have remained stable and unaffected by folding, faulting, or earthquake activity since the time of their deposition.

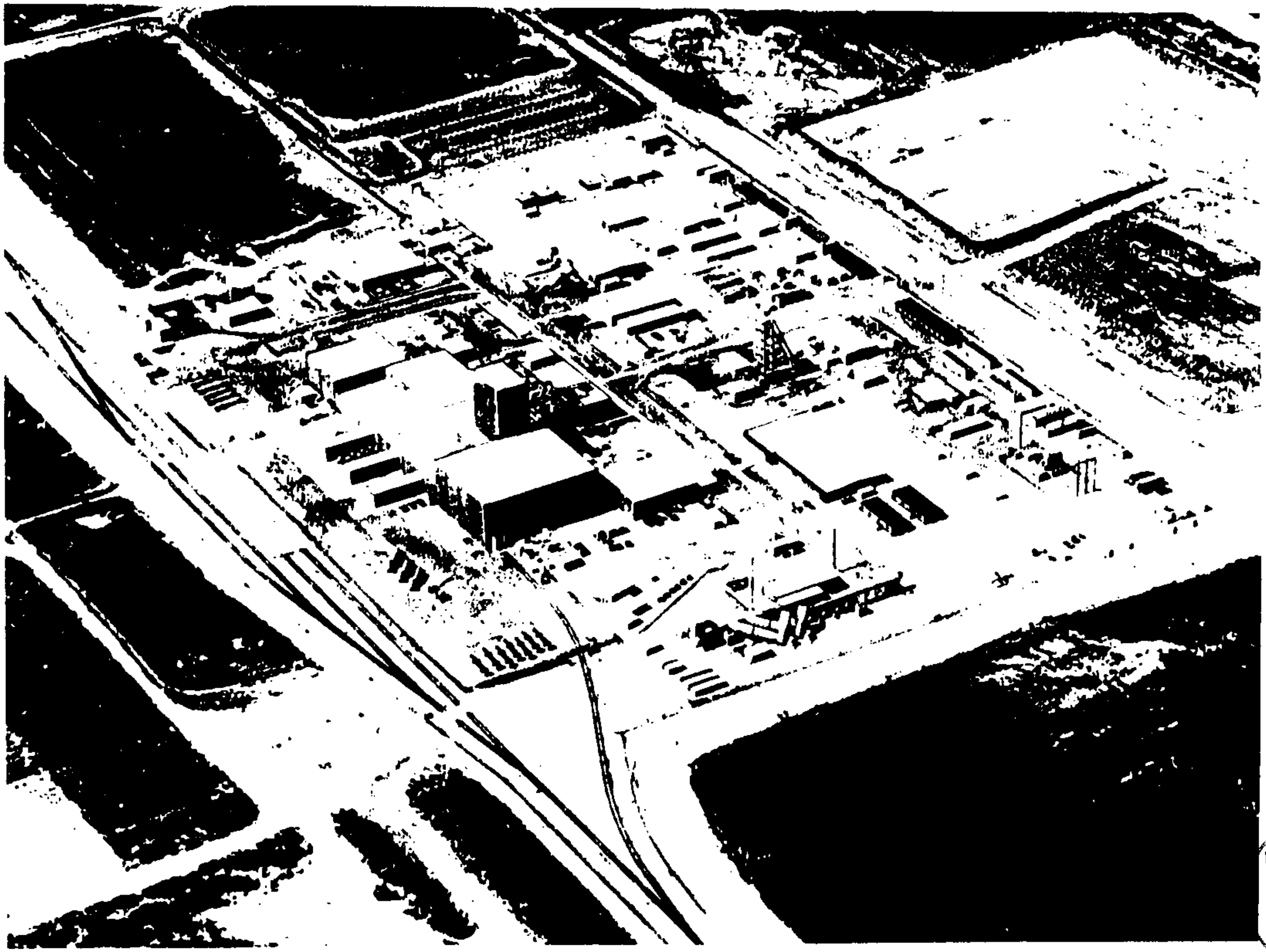


Figure 1-6. Aerial View of the WIPP Surface Facilities Looking to the Northwest.

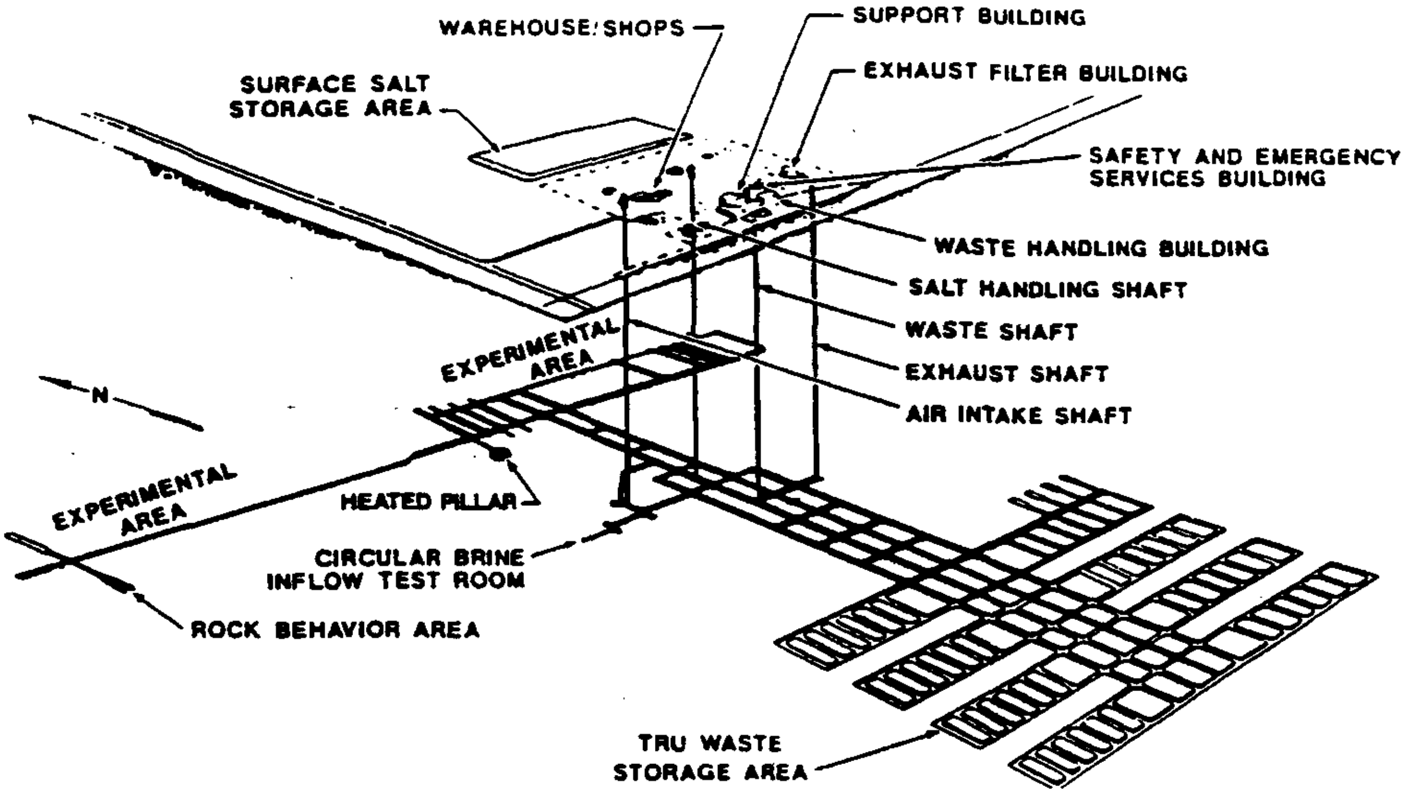


Figure 1-7. **Isometric View of the Surface and Underground Footprint Looking to the Northeast. (Solid lines represent actual underground openings and hollow lines represent proposed waste panels.)**

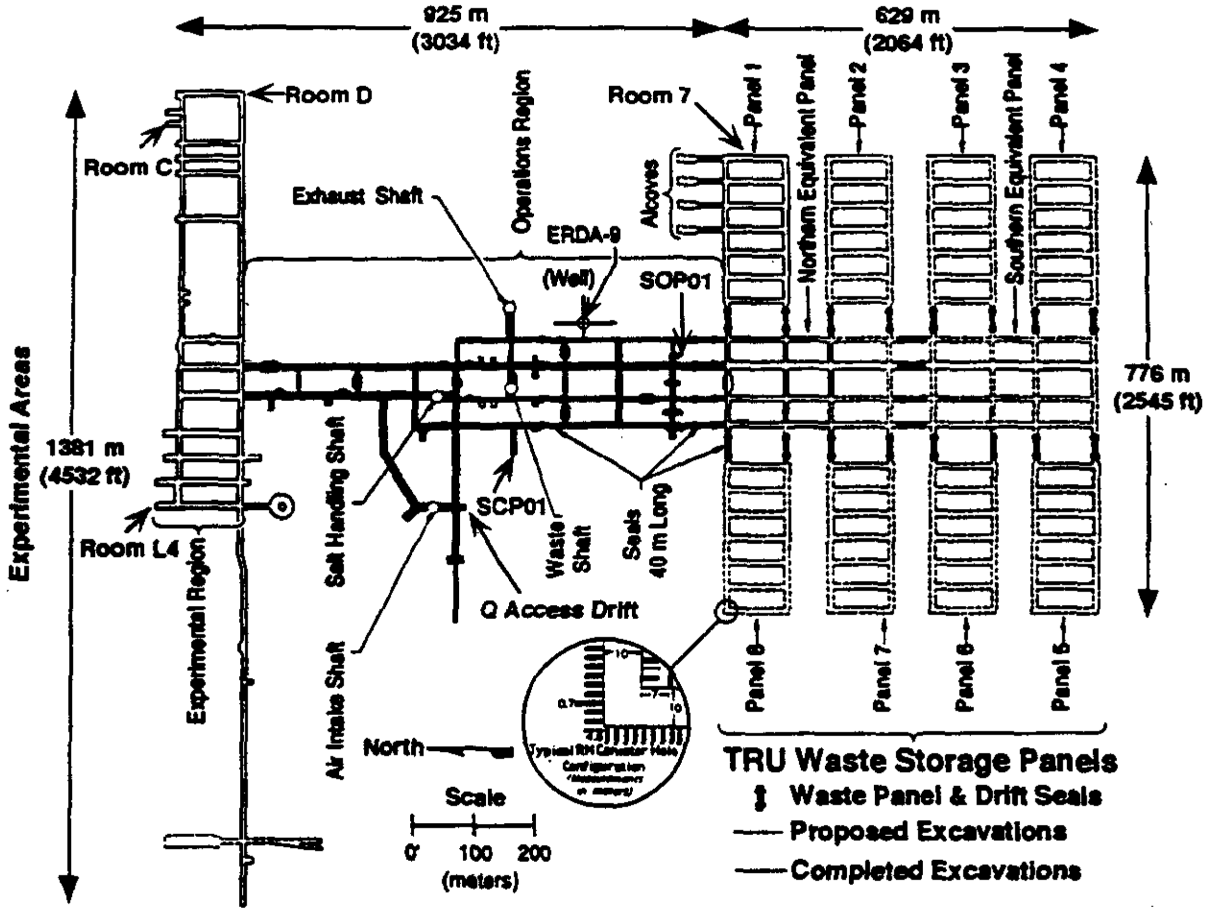


Figure 1-8. Plan View of WIPP Completed and Proposed Excavations.

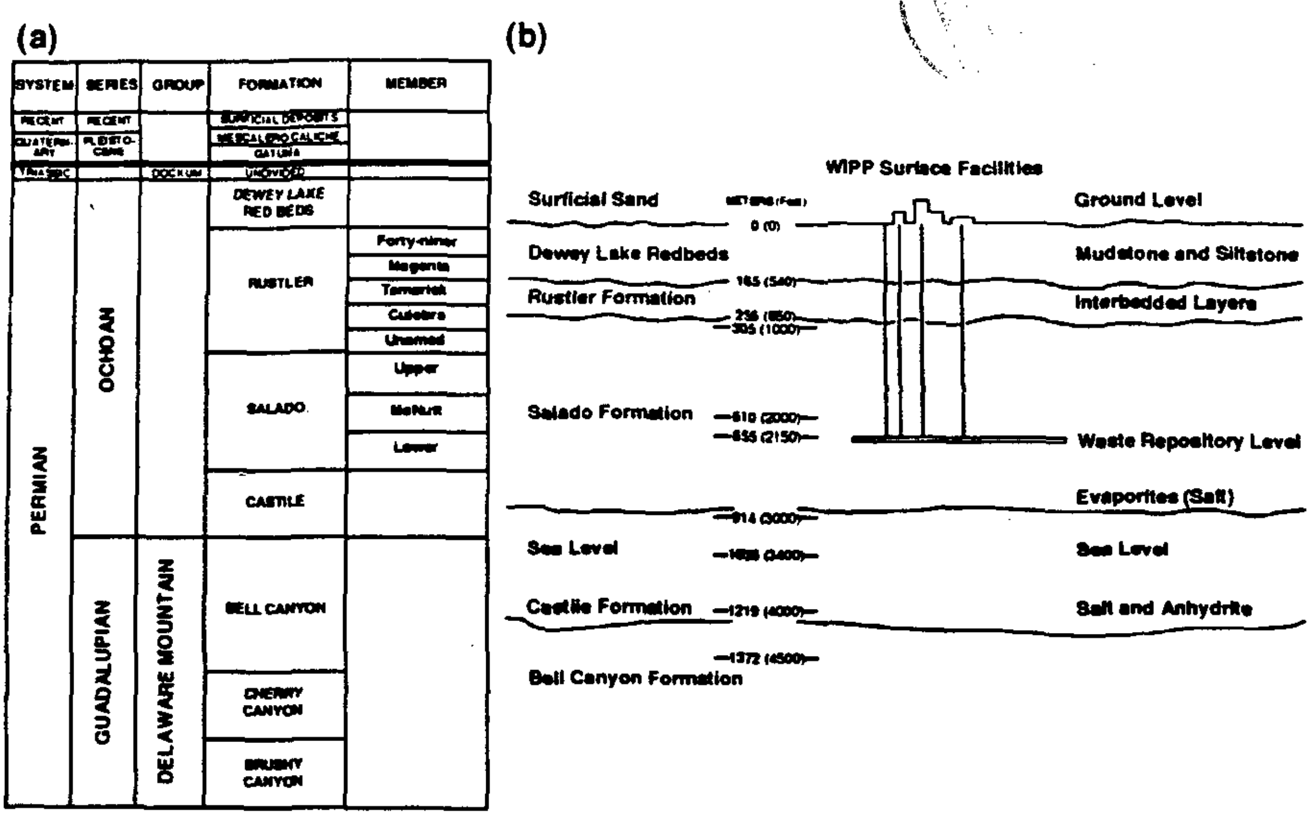


Figure 1-9. (a) WIPP-Area Stratigraphic Column and (b) the Geologic Profile at WIPP Illustrating the Location of the WIPP Underground Workings in the Profile.

1.2.2 WIPP Experimental Programs

Scientific studies and experiments, ongoing at WIPP since 1983, include:

- Thermal/structural interactions (TSI) studies to determine: (1) the stability of the excavated rooms during waste emplacement and possible retrieval, and (2) the long-term deformation of the disposal room and the room's ability to encapsulate the waste (see Section 5);

- Repository plugging and sealing studies designed to develop and test seal materials for the boreholes, shafts, and underground openings (see Section 6);
- Studies to determine important characteristics (e.g., permeability, pore pressures, chemistry of formation fluids) that control transport in the Rustler and Salado Formations (see Section 3);
- Waste package and materials studies to test the safety and performance of waste drums that would hold CH-TRU wastes;
- Brine inflow studies to increase understanding of this phenomenon, since migration of the small amounts of naturally occurring moisture in salt (1 wt % water) to excavated surfaces is important for evaluating the potential for waste container corrosion and waste decomposition (see Sections 5 and 6); and
- Gas generation studies to evaluate type, volumes, and maximum rates of gases generated by corrosion, biodegradation, and radiolysis (see Section 5).

1.2.3 Applicable Regulations and Laws

Details regarding the applicable laws and regulations as they relate to the various phases of the WIPP Project in general (i.e., during both the operational and long-term phases), and to this review effort specifically, will be discussed in Subsection 1.3. In this subsection, applicable laws and regulations are discussed from a historical perspective. Following are the important public laws and associated regulations for the WIPP Project.

- The Atomic Energy Act of 1954, as amended by Reorganization Plan No. 3 of 1970 and the Nuclear Waste Policy Act of 1982. This amended law was the basis for the 40 CFR Part 191 regulations promulgated by EPA in 1985 that deal with the environmental radiation protection standards for the management and disposal of spent nuclear fuel, and high-level and TRU wastes. 40 CFR Part 191 deals with both the operational and the long-term disposal phases of radioactive waste handling, as well as final disposal.

  However, it is the WIPP Project activities for addressing the disposal phase that are the focus of this review and that resulted in the first, second, and third comparisons with the long-term requirements of 40 CFR 191, Subpart B.
- Public Law 91-190, or the National Environmental Policy Act, which was passed in 1970 with regulations issued by EPA in 1978. This law requires that the full environmental impact of proposed projects be evaluated openly with public comment. The regulations for enforcement of NEPA were subsequently promulgated by the Council on Environmental Quality (CEQ). EPA's responsibility for reviewing and publicly commenting on the potential environmental impacts of major Federal action resulted in the 1980 FEIS and the supplement in 1990 (Figure 1-5).
- The Solid Waste Disposal Act (SWDA), as amended by Public law 94-580, the Resource Conservation and Recovery Act, in 1976, and the subsequent Hazardous and Solid Waste Amendments (HSWA) to RCRA (1984). Regulations implementing RCRA were promulgated by EPA and provide for the management of the hazardous waste components of the mixed wastes proposed for disposal at WIPP. 40 CFR 264, Subpart X, applies to the operational phases of the WIPP Project, and land disposal regulations, such as 40 CFR 268, that apply to the testing and disposal phases of the WIPP Project.
- Public Law 96-164, passed by Congress in 1979, authorized WIPP as a US DOE project and defined its research and development mission.

- Public Law 102-579, the WIPP Land Withdrawal Act of 1992 (LWA). This law permanently withdraws the 41.44 sq. km (16 sq. mi) of Federal (i.e., Bureau of Land Management) Lands associated with the WIPP Project (Figure 1-10) from the public domain. The law addresses a broad range of WIPP Project issues, such as the WIPP Test Phase, disposal operations, environmental laws and regulations, waste retrievability, mine safety, transportation, access to information, economic assistance, and miscellaneous payments to the State of New Mexico (DOE/WIPP 89-011, 1993).

The statutory and regulatory requirements for WIPP have changed significantly at the same time as WIPP program work was underway. As illustrated in Figure 1-4, the primary long-term disposal regulations (40 CFR Part 191 and 40 CFR Part 268) applicable to the WIPP Project were passed midway through the construction effort (1983-1989). All this happened after the 1980 FEIS and SAR, and subsequent to the initial design documentation (i.e., the 1981 SPDV) and some of the initial WIPP testing and characterization efforts.

The two sets of regulations (40 CFR 191 and 40 CFR 268) associated with the geologic disposal of mixed wastes have created some uncertainty as to how to proceed in some areas. Several of the requirements that deal with similar topics often suggest different approaches. For example, 40 CFR 268 requires deterministic calculations, whereas 40 CFR 191B is more focused on probabilistic models for achieving confidence in long-term predictions. To reconcile differences in these regulations, DOE has developed a draft Regulatory Criteria Document (RCD 1992) to facilitate disposal and post-disposal decisions for any defense-generated TRU repository. The RCD provides integrated criteria for a common interpretation and approach to the various regulations. DOE plans to use the integrated criteria in the RCD to provide the basis for developing a WIPP-specific regulatory compliance strategy that will guide the planning and conduct of activities at WIPP.

1.2.4 WIPP Performance Assessment

WIPP PAs of the WIPP disposal system will be used to demonstrate compliance with the long-term performance requirements of both 40 CFR 191 and 40 CFR 268.6. It should be noted that PA has specific meanings defined within the context of each of these standards. Long-term PA analyses must be performed and compliance satisfactorily demonstrated before any TRU and TRU mixed wastes can be disposed at WIPP. Furthermore, Section 6 of the LWA requires DOE to publish biennial PA reports that document the long-term performance of WIPP once the test phase at WIPP begins. While additional PAs are needed to demonstrate compliance with the short-term requirement of these regulations and other regulations (e.g., 40 CFR 264, Subpart X), it is the long-term PAs and the approach to their preparation that are the focus of this PART study.

Sandia National Laboratories has been preparing for and conducting preliminary assessments for comparison with the long-term regulatory requirements of 40 CFR 191, Subpart B, since the mid 1980s. The first draft PA forecast was issued in 1989 by Bertram-Howery et al. (SAND88-1452); subsequently first, second, and third comparisons with 40 CFR 191, Subpart B, have been released (Bertram-Howery et al., SAND90-2347, 1990; SNL-SAND91-0893/1,2,3, 1991; SNL-SAND92-0700/1,2,3, 1992). Each of the assessments in the series incorporated new understanding and information gained from the ongoing experimental, site characterization, and PA activities at WIPP.

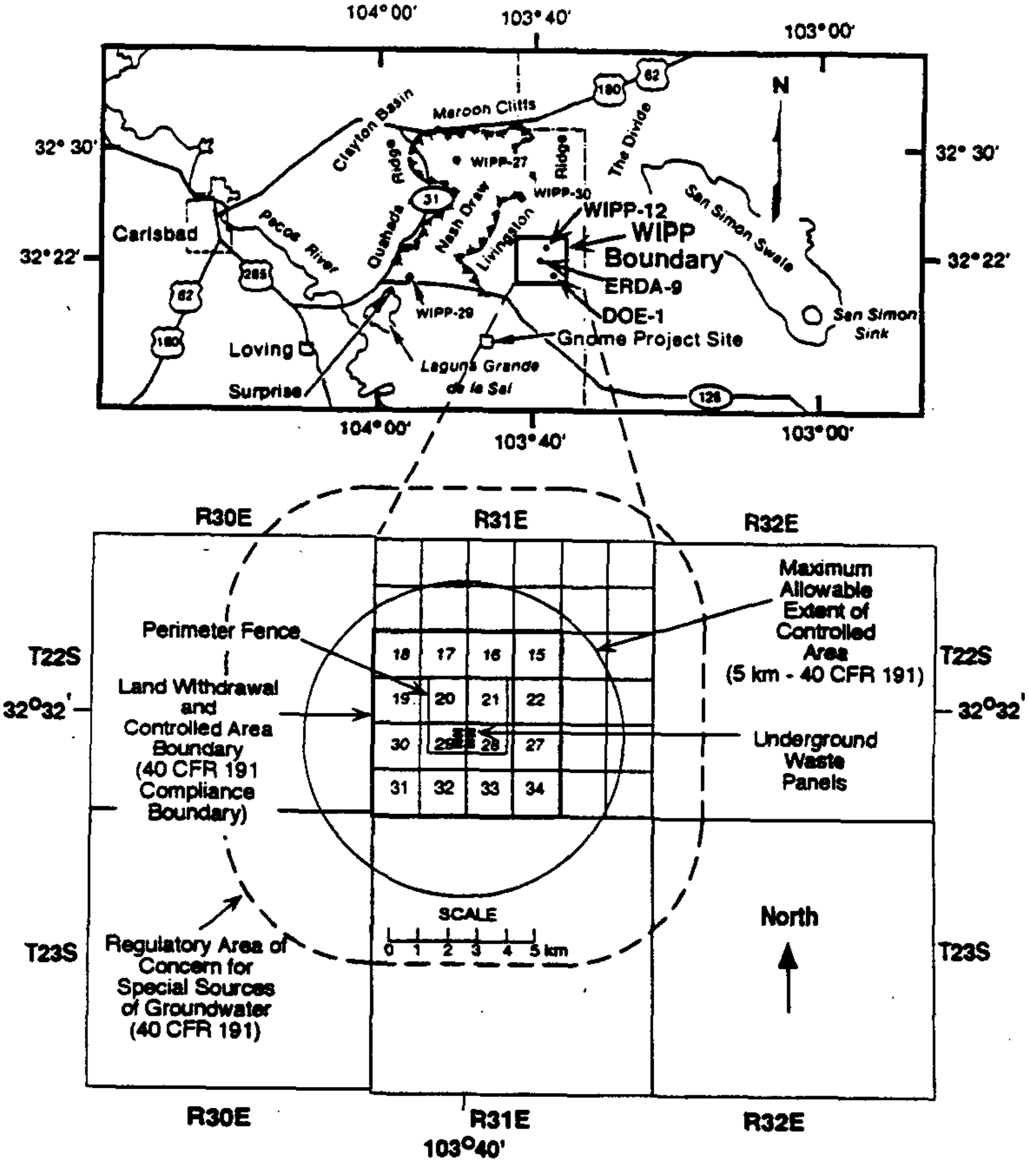


Figure 1-10. Plan View Location Map Showing the Perimeter Fence, Land Withdrawal Boundary, Maximum Allowable Extent of the Controlled Area, and Compliance Boundary (coincident with the land withdrawal boundary) for the WIPP Site Relative to the WIPP Underground Workings.

The Westinghouse Waste Isolation Division (WID) is responsible for performing the PA that documents compliance with the other long-term regulations applicable to the WIPP Project (i.e., those of 40 CFR 268). These land-disposal restrictions prohibit disposal of any hazardous wastes not meeting treatment standards specified by EPA unless, as provided for by 40 CFR 268.6, it can be demonstrated to a reasonable degree of certainty that there will be no migration beyond the disposal unit boundary for as long as the wastes remain hazardous. Because of the nature of the TRU and TRU mixed wastes being considered for the disposal at WIPP, DOE is not currently planning to treat these wastes to meet any of EPA's specified standards, and, as a result, DOE must petition EPA for a no-migration determination (NMD) for the disposal phase. Preliminary sensitivity analyses were undertaken for the WIPP Project Integration Office (WPIO) by Sandia (SNL-SAND92-1933, 1992) to provide project guidance, while the strategy for complying with 40 CFR 268.6 is being developed by WID. Although the specific PA requirements of 40 CFR 268.6 are somewhat different from those of 40 CFR 191, a similar methodology and common data set are envisioned (DOE/WIPP 89-011, 1993).

DOE petitioned EPA (under the provisions of 40 CFR 268.6) in March, 1990, for an NMD, and EPA granted a limited determination for the WIPP test phase (up to 10 years) in November, 1990. This determination permits the emplacement of a limited amount of untreated mixed wastes for testing purposes, but it imposes various conditions that include the issuance of annual NMD reports (DOE/WIPP 91-059, 1991; DOE/WIPP 92-057, 1992), along with the requirement that any emplaced wastes be removed if DOE cannot demonstrate the long-term acceptability of the disposal site by the end of the test period.

1.2.5 WIPP Project Experimental Program

Public Law 96-164 that established the WIPP Project in 1979 authorized the scientific and engineering activities that have been ongoing at WIPP since the FEIS was issued in 1980. This law defined a test phase for the WIPP Project that was to consist of two primary programs (i.e., a PA program and an operations demonstration program) to collect the additional technical data and information necessary for determining whether or not to proceed to the disposal phase of the project. The test phase and the PA program were to investigate the behavior of the salt rock and its interactions with emplaced TRU waste in order to evaluate the long-term performance of the waste disposal system. The operations demonstration program was to demonstrate the safe and efficient handling, transportation, and emplacement of TRU waste in an actual facility.

The test phase at WIPP actually began in 1990, when EPA granted the NMD discussed in the previous section. However, the LWA (Public Law 102-579) defined the test phase as beginning when the first shipment of CH-TRU waste was actually received at WIPP for testing. The LWA required DOE to submit a test phase plan and a waste retrieval plan to EPA within seven months of its enactment and specifically prohibited the transport and emplacement of RH-TRU waste during the test phase. These earlier testing activities at WIPP have since been classified as "pre-test phase" activities and were authorized as discussed in the previous paragraph (DOE/WIPP 89-011, 1993). On October 21, 1993, the Department announced its decision not to conduct tests with radioactive waste at the WIPP facility. Instead, the Department would conduct an enhanced laboratory program to collect the data that was to have been provided by the radioactive waste tests at WIPP. Thus, the test phase, as defined by the WIPP Land Withdrawal Act, will not be conducted. In place of the test phase, the Department *will undertake an experimental program*. The overall purpose of the experimental program is to develop pertinent information and assess whether disposal of TRU waste and TRU mixed waste in the planned WIPP repository can be conducted in compliance with the environmental standards for disposal. The experimental program to be conducted prior to the disposal phase encompasses (1) performance assessment conducted to evaluate compliance with the applicable EPA regulations; (2) studies designed to provide the scientific basis or enhance confidence in performance assessments; and (3) the process by which the decision will be made as to whether TRU waste can be emplaced in the repository for permanent disposal.

1.2.6 Other WIPP Project Phases

The WIPP Project has been developed in distinct phases.

- Siting Phase. The earliest, or siting, phase of the project was protracted. As illustrated in Figure 1-4, it began with feasibility studies initiated in the early 1950s and identified salt as a medium for permanent disposal in 1956. The Permian Basin was identified in 1962; investigations of the WIPP area began in 1974; and finally, the WIPP site was formally selected in 1979 with the passage of Public Law 96-164. The siting phase officially ended in 1980 with the publication of the FEIS.
- Design (or SPDV) Phase. The site and preliminary design validation program that began in 1981 followed from the DOE Record of Decision (DOE, 1981). This SPDV program involved some initial construction and development at the WIPP site, starting in 1981. Two shafts were sunk to excavate an underground testing area and at that time various geologic, hydrologic, and geotechnical studies were initiated.
- Construction Phase. Full-scale construction began at the site in 1983 and was completed in 1989. This phase formally ended with publication of the Final Supplemental Environmental Impact Statement (FSEIS) and the Final Safety Analysis Report (FSAR) in 1990.
- Predisposal Phase. This phase encompasses the time frame during which experimental activities gathering information needed to support the compliance application through performance assessment calculations will be completed. These calculations are an integral part of compliance with 40 CFR Part 191 and 40 CFR Part 268.6. This time frame also includes the preparation of the compliance documents, establishment of the administrative record, submission of required documents and applications to EPA, and appropriate rulemaking by EPA. During this period, other key WIPP program activities required to support a WIPP disposal decision must also be completed.
- Disposal Phase. This phase would follow the WIPP test phase if a decision to dispose is reached by DOE after demonstration of compliance with applicable laws, regulations, and other requirements. This phase is expected to last approximately twenty years and would begin with the first emplacement of the waste and end with the emplacement of the last panel seal that contacts the waste.
- Decommissioning Phase. This phase, expected to take approximately ten years, includes the time from the emplacement of the last panel seal that contacts the waste through the emplacement of the last shaft seal.
- Post-Decommissioning Phase. This final phase is the 10,000-year period following the decommissioning phase.

1.2.7 WIPP Oversight/Regulatory Groups and Review

Since 1979, the WIPP Project has received independent technical review from the Environmental Evaluation Group (EEG). This oversight function was established by Congress (Public Law 100-456) with funding provided by DOE. The EEG has conducted and published review comments on all major WIPP Project activities and produced more than fifty reports and more than twenty papers on all aspects of the Project (i.e., the site, design and operation, transportation, and long-term integrity). The EEG also conducts independent environmental surveillance on- and off-site by obtaining their own samples of water, soil, biota, and air (e.g., EEG's air sampling equipment is located next to DOE's) or using samples obtained by the WIPP Regulatory and Environmental Programs. EEG is expected to continue to function during the test phase and is given specific authority by the LWA (e.g., to review and comment on the biennial PA during the test phase).

In 1981, DOE and the State of New Mexico entered into an agreement for consultation and cooperation (DOE and State of New Mexico, 1981) that was amended in 1984, 1987, and 1988. This agreement includes provisions for State involvement in oversight and consultation, imposes requirements on DOE with regard to development and operation of WIPP (e.g., waste retrievability), and specifies provisions for involvement of the State in the WIPP Project {DOE/WIPP 89-011, 1993}). The State of New Mexico exercises its oversight, consultation, regulatory, and monitoring functions through various state agencies. (1) The New Mexico Environmental Department (NMED) regulates WIPP activities under the New Mexico Hazardous Waste Act, the New Mexico Water Quality Act, and the New Mexico Air Control Act. NMED reviews and controls various activities at WIPP for the State and also for the EPA under RCRA, based on authority provided by EPA. During the test phase, NMED will review and comment on the biennial PA developed by DOE and will annually review DOE's basis for retrievability. The New Mexico Bureau of Mines is responsible for inspection of WIPP mining activities, and the New Mexico Highway and Transportation Department is responsible for highway routing.

A variety of other external groups and agencies, besides the EEG and the State of New Mexico, have provided independent oversight and review of various aspects of the WIPP Project. For example, the NAS has a standing panel on WIPP which has repeatedly reviewed the project. The panel consists of scientists and technical experts from various relevant fields. NAS has been involved in site selection and characterization. The NAS WIPP Panel provides quarterly reviews that have covered repository PA, pre-operational test activities, geotechnical issues, and hydrologic issues. The NAS WIPP Panel reports to the NAS Board on Radioactive Waste Management that, in turn, makes recommendations to DOE and Congress. The NAS Panel also provides comments to Congress. NAS has continuing authority under the LWA to provide oversight and review of the WIPP Project. Some of these are required by the LWA, which assigned specific regulatory and oversight responsibilities to various groups including State and Federal agencies. For example, the EPA is assigned as the certifying agency by the LWA. The EPA must (1) certify compliance with the 40 CFR 191; (2) determine compliance with the RCRA/No-Migration Determination; (3) approve by rule the Test Phase Plan; and (4) approve by rule the Retrieval Plan.

This PART review further illustrates DOE's routine use of outside technical expertise to examine various aspects of the WIPP Project.

Following are various other WIPP oversight and review groups, along with a brief description of their function.

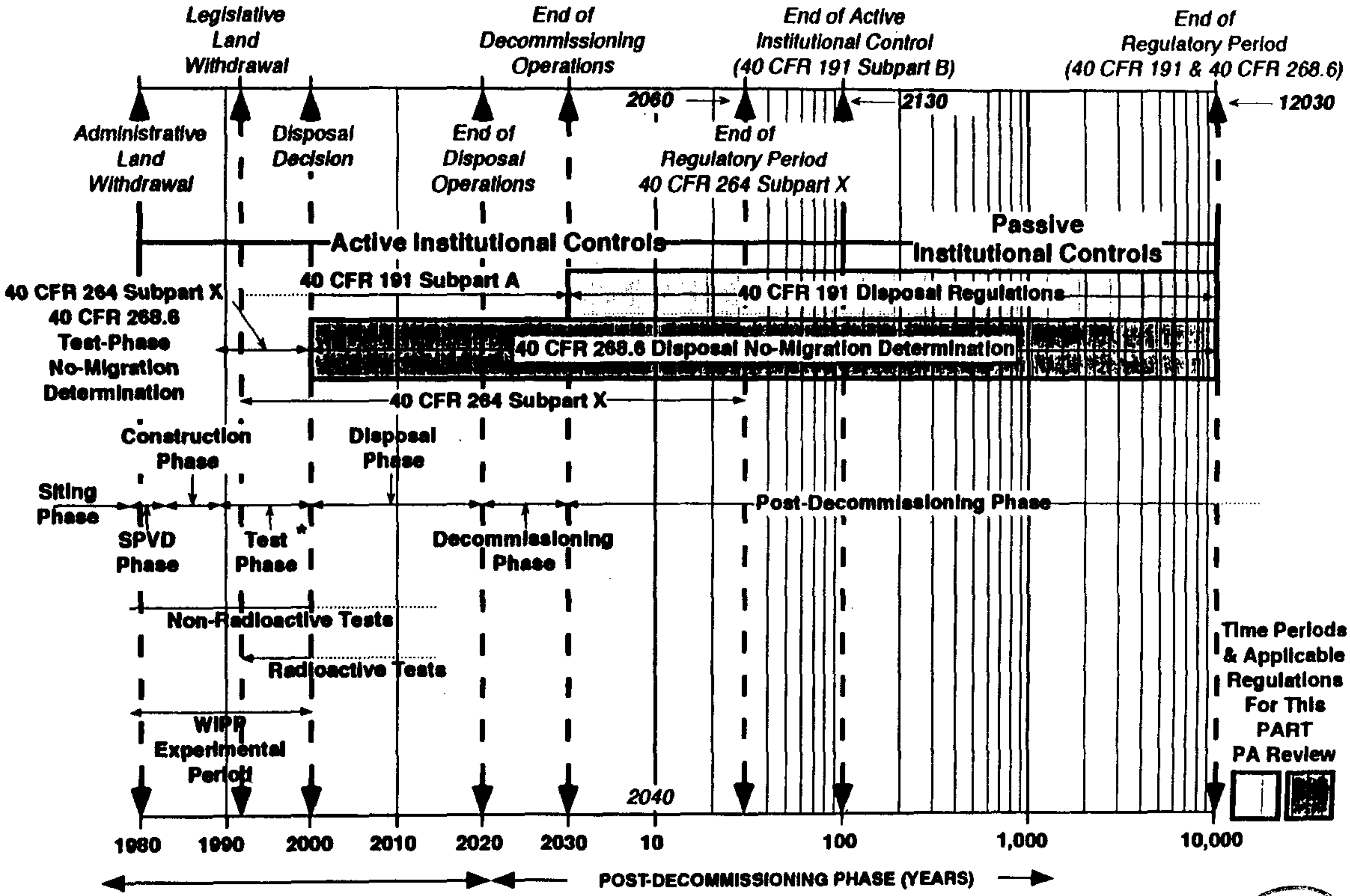
- The Defense Nuclear Facility Safety Board (DNFSB) was established by Congress in 1988 to review and evaluate the content and implementation of DOE standards relating to the design, construction, operation, and decommissioning of defense nuclear facilities. The DNFSB provides DOE oversight in the form of operational safety reviews.
- The Occupational Safety and Health Administration (OSHA) has specific regulatory and oversight responsibility with regard to emergency response training by the LWA.
- The National Institute of Occupational Safety and Health (NIOSH) also has specific regulatory and oversight responsibility with regard to emergency response training by the LWA.
- The Mine Safety and Health Administration has specific regulatory and oversight responsibility with regard to underground room stability and mine safety by the LWA.
- The Nuclear Regulatory Commission (NRC) is assigned specific regulatory and oversight responsibility with regard to transportation casks by the LWA.
- The Bureau of Mines has specific regulatory and oversight responsibility with regard to underground safety by the LWA.
- The Bureau of Land Management provides DOE with consultation and oversight on lands issues.
- The Blue Ribbon Panel (disbanded in November 1991), provided review/guidance on waste characterization, the Waste Acceptance Criteria Certification Committee, the test phase program, the test phase plan, and long-term safety.
- The Advisory Committee on Nuclear Facility Safety (also disbanded in November of 1991) provided guidance on operational and long-term safety.

1.3 REGULATIONS CONSIDERED IN PART REVIEW

Figure 1-11 is a time-line that illustrates the relationships between the key regulations applicable to the WIPP Project during the various project phases and identifies plausible dates and regulatory time periods; (the actual dates are for reference purposes only and do not reflect any established schedule). The PART review examined the adequacy of the current PA program at WIPP for addressing the two long-term regulatory requirements. These specific regulations are shaded in Figure 1-11 to illustrate the applicable time periods and the phases of repository development to which they apply.

- The long-term regulation that applies to the radioactive components of the proposed waste – 40 CFR 191 Subpart B, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Waste, applies to the post-decommissioning phase of repository development.
- The long-term regulation that applies to the hazardous constituents of the proposed waste – 40 CFR 268.6, Land Disposal Restrictions of the RCRA—applies to the disposal, decommissioning, and post-decommissioning phases of repository development.

At the time that the PART review was conducted, SNL had the primary responsibility for supporting the WIPP testing program and performing the PA for DOE with regard to evaluating compliance of the WIPP with 40 CFR 191 Subpart B. External technical review of these SNL activities is provided by a special panel from the National Research Council/National Academy of



NOTE: This schematic is meant to show sequence; the years are identified to indicate relative timing and should not be interpreted as a schedule.

***Test Phase as defined in Legislative Land Withdrawal Act**

Figure 1-11. Time-Line Showing the Relationships Between the Various Phases of the WIPP Project and the Applicable Regulations and Their Periods of Applicability. Note that the shaded regulations, project phases, and time periods are the focus of this PART review.

Sciences. SNL also supports DOE in these same activities with regard to RCRA 40 CFR 268.6 regulations. WID is responsible for supporting the WIPP activities with respect to evaluating compliance with both the short- and long-term needs of the 40 CFR 268.6 regulations and, as mentioned earlier, prepares the annual Test Phase NMD report to the EPA. As the managing and operating contractor, WID is also responsible for preparing the no-migration variance petition (NMVP) required for the disposal, decommissioning, and post-decommissioning phases. WID is thus responsible for performing the PA to evaluate whether the WIPP is expected to comply with the regulations during these additional phases of repository development; if so, WID must prepare the NMVP used to demonstrate compliance with this RCRA regulation (40 CFR 268.6). The PART has reviewed SNL and WID activities relative to the PA needs of both of these sets of regulations.

This subsection contrasts the differences in approach and specific requirements of the two long-term regulations as they relate to WIPP. Ambiguities and differences between 40 CFR 191 and RCRA regulations were reconciled by DOE into integrated criteria in the draft RCD in December, 1992. These draft integrated criteria have been examined by PART to determine the applicable subset, given the specific purpose of the PART review (Appendix A lists this subset).

1.3.1 40 CFR Part 268.6 Approach

The RCRA land disposal restrictions of 40 CFR Part 268.6 that apply to the hazardous constituents of the mixed wastes proposed for disposal at WIPP are very detailed. The regulation depends on process knowledge and control of the waste form to ensure disposal safety. It requires characterization of the waste so that specific treatment methods can be selected and carried out prior to emplacement of the treated waste in or on the land. To emplace any untreated waste, as is planned at WIPP, DOE must petition for and be granted an exemption under 40 CFR 268.6. This petition must demonstrate, "to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit or injection zone for as long as the wastes remain hazardous." This allowance for a petition for "no-migration" or the "no-migration determination" (NMD), recognizes the need for flexibility in applying the concept of proper waste treatment before land disposal.

1.3.2 Specific Requirements of 40 CFR 268.6

The petition to allow disposal of prohibited (i.e., untreated) waste under 40 CFR 268.6 requires a demonstration of no migration, as discussed above. The important requirements for this demonstration include the following:

- Identification of the specific disposal unit and the specific waste;
- Chemical and physical characterization of waste to be disposed and a comprehensive characterization of the disposal unit's chemical and physical parameters and current environmental conditions, using approved methods for sampling, testing, and estimation that are as accurate and reproducible as possible;
- Simulation models for the site and waste that have been calibrated and verified for accuracy through comparisons with measurements for demonstrating compliance with the no migration provision;

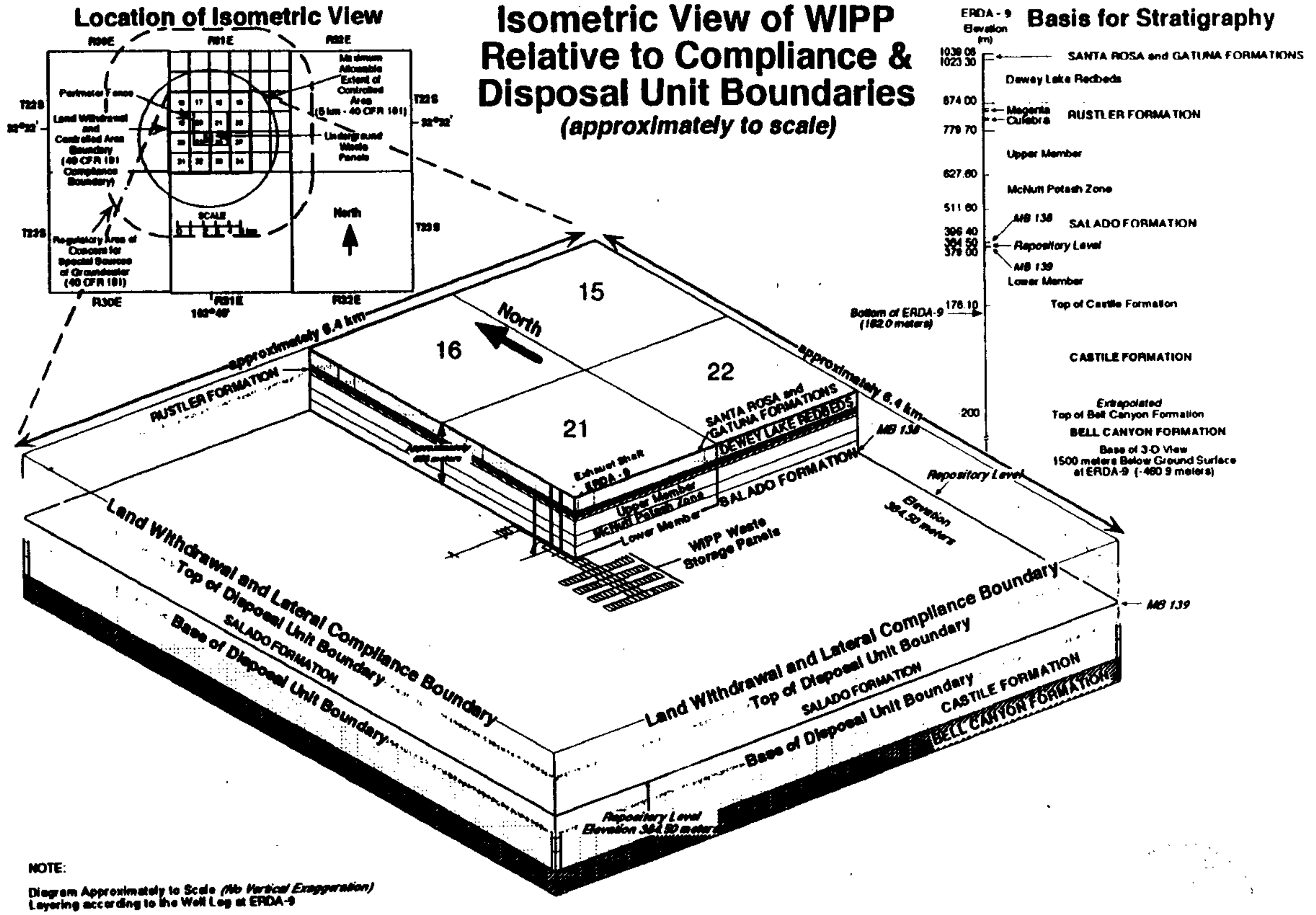
- Analyses that identify and quantify the uncertainty in the various aspects of this demonstration, including evaluation of the consequences of predictable future events (e.g., earthquakes, floods, other natural phenomena);
- A detailed monitoring plan for detection of migration at the earliest possible time; and
- Quality assurance and a quality control plan for all aspects of demonstration.

The current regulation (40 CFR 268.6) is not specific with regard to what constitutes no-migration, the disposal unit, the time period (i.e., "as long as the waste remains hazardous"), or reasonable degree of certainty. Additionally, there is no approved guidance with regard to the modeling and preparation of the no-migration variance petition and no specific discussion as to whether the consequences of human intrusion must be addressed as a possible future event and system state as part of the no-migration demonstration. Some of these issues were and are in the process of being resolved as a result of the following:

- The conditional NMD for the activities of the test phase period at WIPP that DOE was granted in 1990 (EPA, 1990; Federal Register Vol. 55 No. 220, 47,700-47,721);
- EPA's recently published draft of a guidance manual for petitioners seeking no-migration variances (EPA, 1992; EPA 530-R-92-023), by providing EPA's interpretations and suggested procedures for compliance with 40 CFR 268.6 (DOE/WIPP 89-001, 1993); (however, PART has not yet completed formal review of the guidance); and
- Proposed rulemaking for the revisions to the no-migration standard published in the *Federal Register*, August 11, 1992.

Following are current definitions or interpretations by DOE of the important issues:

- Disposal unit. The 40 CFR 268.6 disposal unit boundary for WIPP has been interpreted to extend vertically from the top to the bottom of the host rock (the Salado Formation) and laterally where the 6.44 km x 6.44 km (4 mi x 4 mi) land withdrawal boundary cuts through the host rock, as shown in **Figure 1-12.**
- As long as the waste remains hazardous. The demonstration of no-migration for a period *of 10,000 years has been interpreted to be sufficiently long.*
- No-migration. No-migration is concentration- and not detection-based; (i.e., no-migration means no movement of concentrations above health-based levels beyond disposal unit boundaries).
- Reasonable degree of certainty. 40 CFR 268.6(a) A reasonable degree of certainty will be delineated through discussions between DOE and EPA and through technical and public review and comment on a proposed NMD. The delineation will pertain primarily to the adequacy and completeness of information provided to the regulatory by DOE, which will be the basis for an EPA determination. The adequacy and appropriateness of simulation modeling and associated assumptions and uncertainties are key to this definition. Uncertainties will be systematically evaluated. Since uncertainty will always exist in any analysis of events occurring in a 10,000-year time frame, it is important that the implications of the uncertainties in regard to repository performance evaluations be understood.
- Modeling and analysis. The regulation (40 CFR 268.6) is not specific with regard to whether a deterministic or a probabilistic modeling approach is required. However, the wording of the regulation—"Simulation models must be calibrated for the specific waste and site conditions, and verified for accuracy by comparison with actual measurements"—implies that a deterministic approach is expected. The regulation also clearly indicates that a sensitivity and uncertainty analysis is required to identify and quantify any aspects of the demonstration that contribute significantly to uncertainty" for current and predictable future conditions.



NOTE:
Diagram Approximately to Scale *(No Vertical Exaggeration)*
Layering according to the Well Log at ERDA-9

Figure 1-12. **Isometric View of WIPP Relative to Compliance and Disposal Unit Boundaries.**

- Human intrusion. The regulation requires that "This analysis must include an evaluation of the consequences of predictable future events, including, but not limited to, earthquakes, floods, severe storm events, droughts, or other natural phenomena." This language seems to exclude an examination of the consequences of human intrusion (unless inadvertent human intrusion is considered to be a predictable future event or natural phenomenon). This interpretation is also supported by the guidance (EPA, 1992; EPA 530-R-92-023) for preparing the no-migration petition. The guidance does not require inadvertent human intrusion to be considered in the demonstration.

1.3.3 40 CFR 191 Subpart B Approach

In contrast to 40 CFR 268.6 regulations, the environmental radiation protection standards of 40 CFR 191 through Subpart B define environmental standards for geologic disposal that are more general in that they do not place specific restrictions on the type of radioactive materials that can be disposed or how they can be disposed. Instead, this regulation requires the "disposal system" (i.e., any combination of engineered and natural barriers that isolate the waste) to comply with the four different requirements of 40 CFR 191 Subpart B, shown graphically in **Figure 1-13**. The containment requirements (§191.13) and the two protection requirements (individual, §191.15, and ground water, §191.16) are quantitative and begin as follows: "Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation."

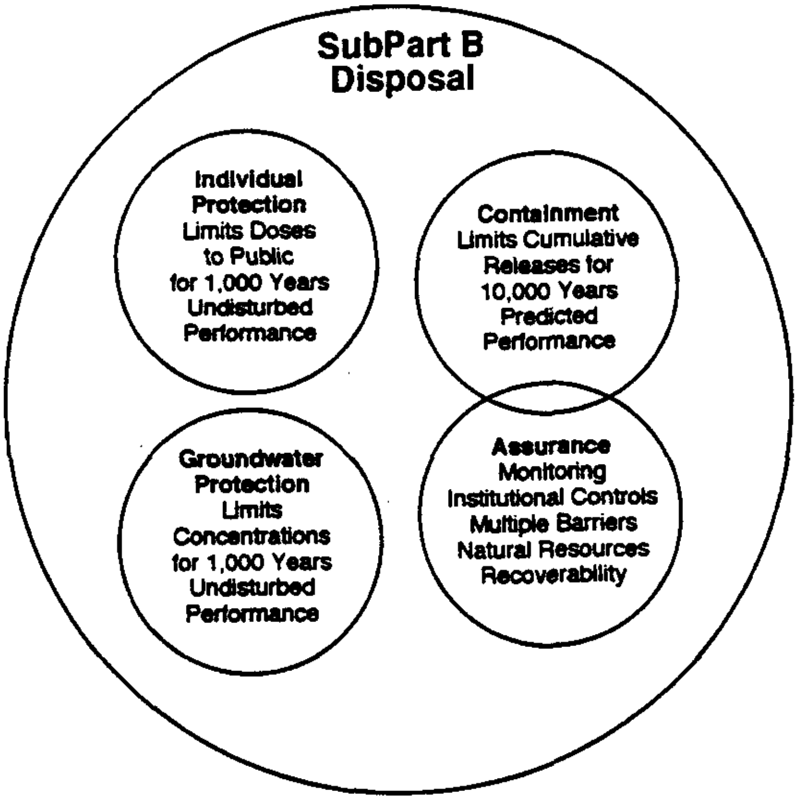


Figure 1-13. Graphical Representation of the Four Requirements of Subpart B of 40 CFR Part 191 (after Sandia 1993; SAND92-0700/1) Illustrating the Overlapping of the containment Requirements Will Be Met Containment and Assurance Requirements to Increase Confidence that the C.

They then go on to describe what different numerical criteria must be met to satisfy each of the different sections: limited cumulative releases, limited doses, and limited concentrations. The assurance requirement (§191.14), through its provisions for design (e.g., multiple barriers, recoverability), for monitoring, for the use of active and passive institutional controls, and for evaluating adverse factors related to site selection (e.g., natural resources and exploration potential), was developed to provide additional confidence that the long-term compliance (10,000 years) with the containment requirements of §191.13 can be met.

1.3.4 Specific Requirements of 40 CFR 191 Subpart B

Following are the important requirements for this regulation.

- The Federal Government is committed to permanent ownership of the disposal site.
- Active institutional control of the disposal site will be maintained for as long as practicable; (PA must assume loss of active control after 100 years).
- Passive institutional control of disposal sites will be maintained through permanent markering, records, and other means "to indicate dangers of wastes and their location."
- Disposal site selection must avoid places "where there is a reasonable expectation of exploration for scarce or easily accessible resources" unless this exploration potential is compensated for by the site's favorable characteristics.
- Disposal system designs must include multiple engineered and natural barriers to isolate wastes, and the design must not preclude removal for a reasonable period of time after disposal.
- The disposal system must be monitored after disposal "to detect substantial and detrimental deviations from expected performance" in ways "that do not jeopardize isolation of the wastes" until any significant concerns are addressed.
- Performance modeling must be provided to show compliance with the numerical requirements of §191.13, §191.15, and §191.16. A probabilistic modeling approach that evaluates long-term (decommissioning to 10,000 years) predictions of disposal system performance is specified as well as implied. This evaluation of performance must identify all the significant processes and events (probability greater than one chance in 10,000 of occurring in 10,000 years) that could affect the disposal system. The evaluation must account for the associated uncertainties (of determining the likelihood of events, of understanding the various processes, of developing conceptual models, and of determining the parameters) and examine the effects that these uncertainties have on predicted performance of the total disposal system; (all portions, both natural and engineered, should be considered even if the performance is uncertain).

  Compliance with the numerical containment requirements (§191.13) is to be through a single "complementary cumulative distribution function" (CCDF) that considers both disturbed and undisturbed conditions. Compliance with the individual and groundwater protection requirements (§191.15 & 191.16) will be based upon "best estimate" predictions (i.e., the mean or median of the appropriate distribution, whichever is higher) for "undisturbed conditions" (i.e., not disrupted by human intrusion or unlikely natural events). It should be noted that the probability cutoff for unlikely events is not specifically defined.
- Inadvertent human intrusion must be considered. Inadvertent human intrusion into the repository by exploratory drilling (no greater than 30 boreholes per square km per 10,000 years in sedimentary geologic formations and 3 boreholes per square kilometer

per 10,000 years in other geologic formations), which is soon realized by the intruders, is the most severe intrusion scenario that needs to be assumed.

It should be noted that unlike the applicable RCRA regulation (40 CFR 268.6), 40 CFR 191 Subpart B does not call for specific quality assurance or a quality control plan. (The significance of this is discussed in Section 8.)

In contrast to the RCRA no-migration regulation (40 CFR 268.6), the wording of 40 CFR 191 Subpart B (§191.13-16), its definitions (§191.12), and the wording in the guidance for its implementation (Appendix B of the regulation) are generally much more specific regarding the issues that were of concern in the RCRA no-migration regulation: compliance boundary, time periods of concern, reasonable expectation, modeling-analysis approach, and human intrusion. Following are current interpretations of these equivalent issues for 40 CFR 191 Subpart B.

- Compliance boundary. The maximum allowable compliance boundary under §191.13 and §191.15 is defined as the accessible environment, which is the atmosphere, land surfaces, surface-water, oceans, and all the lithosphere beyond the controlled area. The controlled area is all the subsurface underlying a surface location that must be identified by passive institutional controls, encompassing no more than 100 square km and extending no more that 5 km (3 mi) beyond the outer boundary of any emplaced wastes. For WIPP this maximum allowable extent boundary is as shown in Figure 1-10. However, for WIPP only the 6.44 km x 6.44 km (4 mi x 4 mi) land withdrawal boundary will be marked by passive institutional controls, and so the accessible environment (or compliance boundary) becomes the entire land surface and atmosphere and all of the rest of the environment beyond this land withdrawal boundary. Figure 1-12 is a cutaway isometric view of the WIPP site, showing the subsurface stratigraphy drawn approximately to scale according to the interpretations of the ERDA-9 borehole. The drawing, which is also approximately to scale, shows the WIPP completed and proposed subsurface excavations, as well as the location where the 6.44 km x 6.44 km (4 mi x 4 mi) land withdrawal boundary cuts through the subsurface to form the lateral limits of the non-accessible environment, which forms the vertical compliance boundary with the accessible environment. The land surface within the 6.44 km x 6.44 km (4 mi x 4 mi) land withdrawal boundary forms the upper compliance boundary that separates the non-accessible subsurface environment from the accessible environment above.
- Reasonable expectation. There is no explicit interpretation or guidance regarding the meaning of this phrase. However, the wording of both Part B of the containment requirement (§191.13) and the guidance for implementation of the regulation (Appendix B) clearly indicates that EPA requires a reasonable expectation, on the basis of the record before the implementing agency, that compliance with §191.13(a) will be achieved. The guidance for this regulation indicates that the implementing agency is expected to use prevalent expert judgment in making the various numerical predictions and that "the implementing agency may choose to supplement such predictions with qualitative judgments as well."
- Modeling-analysis approach. As discussed above, a probabilistic modeling approach is specified for the containment requirement (§191.13) and implied by the wording for the individual (§191.15) and groundwater (§191.16) protection requirements.
- Human intrusion. Inadvertent human intrusion must be specifically addressed, as discussed above.

1.3.5 Concerns Related to the Regulations

DOE and EPA will be treading on new regulatory ground as the WIPP project moves forward. Furthermore, there are basic differences in these regulations that have yet to be resolved. Some of the concerns include the following:

- the question of whether there is a need to evaluate the consequences of inadvertent human intrusion as part of the no-migration demonstration for 40 CFR 268.6;
- the need to get precise definitions and interpretations for important regulatory and guidance terms (e.g., "likely", "unlikely") and concepts (e.g., calibration and verification for accuracy through comparisons with measurements, when such long time periods are involved);
- the lack of specified Quality Assurance (QA) requirements for 40 CFR 191 Subpart B (should be contained in 40 CFR 194, which is currently being developed by EPA);
- the need for identification of the specific waste with a chemical and physical characterization as part of the demonstration for 40 CFR 268.6 when a good fraction of the waste has not been generated;
- possible conflict between the requirement for a detailed monitoring plan for detection of migration at the earliest possible time for 40 CFR 268.6 and the long-term disposal concerns that monitoring can jeopardize the isolation of the wastes; and
- the need to develop consensus on the meaning of "reasonable expectation" and "reasonable degree of certainty."

1.4 PART APPROACH

This subsection discusses the organization of the PART, what was reviewed, and the process used to perform the review. It also briefly discusses the role of the Golder simplified PA modeling approach and the planned assessments.

The PART effort consists of periodic briefings to WIPP Project Division, Office of EM-342, and this final report issued to the Director, EM-342. To prepare the report, PART members have:

- Performed a limited review of relevant PA and PA-related literature and on-going PA efforts, including discussions with WPIO, WID compliance staff, and the SNL PA staff, their principal investigators, and their contractors;
- Evaluated the conceptual models and input parameters used in the PA analyses that describe the site conditions for the repository system and the processes involved;
- Evaluated the level of confidence associated with the performance predictions that the repository system will meet 10,000-year performance requirements; and
- Begun development and use of a simplified PA model for verifying SNL PA analysis, and evaluated the effect of alternative conceptual models, parameter distributions, etc., that were identified during the review.

[The results of the PART effort will be issued as two separate reports so that PART recommendations can be considered for 1994 PA activities.] This first report documents the PART evaluation of the adequacy of the current PA program for meeting 40 CFR 191 and 40 CFR 268.6 requirements, and contains PART recommendations for improving the PA program. The second report will document the results of the verification analysis and describe the simplified PA models and methodology used, results of the verification analysis, and significant discrepancies, alternative models, etc., identified by the PART.

1.4.1 PART Organization

The Director of EM-342 and the PART Chairperson selected the PART members on the basis of their knowledge of components and processes associated with salt repository and their independence from the WIPP Project. More specific criteria included (1) familiarity with geologic repositories, especially salt; (2) PA expertise or knowledge of risk assessment techniques; (3) knowledge of RCRA and/or 40 CFR 191 requirements; and (4) no direct association with any of the PA activities for the WIPP.

PART members, their assignment, affiliation, and area of expertise are as follows:

DUTY & Name	AFFILIATION	AREA OF EXPERTISE
Chairperson		
Bryan Bower	US Department of Energy	Site Operations, Test Programs, and PA
Deputy Chairperson		
Charles Voss	Golder Associates Inc.	Engineered Barriers
Members:		
James Russell	Texas A&M University	Creep and Room Closure
Neville Carter	Texas A&M University	Brine Migration
Pamela Doctor	Pacific Northwest Laboratory	PA Methodology
Charles Cole	Pacific Northwest Laboratory	Flow and Transport

1.4.2 WIPP Participation

The following WIPP Project organizations participated in this review:

- EM-342. The Director, EM-342 authorized the PART review and report for management purposes.
- WPIO. The WIPP Project Integration Office provided administrative support in assembling reference material from SNL and WID, scheduled the interviews with the SNL Performance Assessment staff, and coordinated the WPIO, the WIPP Project Site Office (WPSO) and SNL review of the draft PART Report.
- WPSO. The WIPP Project Site Office provided administrative support by scheduling interviews with the WID compliance staff and coordinating the WPSO and WID review of the draft PART Report.
- SNL. Sandia National Laboratories provided the reference material required to support the independent review, made members of its staff available for interviews by the PART, clarified written documentation, answered specific questions, and coordinated the review of the draft PART Report by their staff as directed by WPIO.
- WID. Westinghouse Waste Isolation Division provided the reference material required to support the independent review, made members of its staff available for interviews by the PART, clarified written documentation, answered specific questions, and coordinated the review of the draft PART Report by their staff as directed by WPIO.

1.4.3 Basis of the Review

Members of the PART have used, to the extent possible, the latest information available to carry out this limited review of the WIPP PA Program. Sources of information include (1) the base (or minimal) set of documents listed below; (2) a WIPP site tour; (3) a series of interviews with various SNL, WPIO, WID, and EEG staff; and (4) any other relevant documents or reference material that the PART identified as relevant in the course of their review. The EM-342 PA Manager coordinated the assembly and distribution of the reference material required for the review with the appropriate WPIO managers.

PART members, at a minimum, have had access to the following base set of information: SAND92-0700/1-3 Preliminary Comparison with 40 CFR 191, Subpart B for the Waste Isolation Pilot Plant, December 1992, Volumes 1-3; SAND91-0893/1-4 Preliminary Comparison with 40 CFR 191, Subpart B for the Waste Isolation Pilot Plant, December 1991, Volumes 1-4; WIPP Waste Characterization Program Plan; WIPP Waste Analysis Plan; WIPP Test Phase Plan; Technical Needs Assessment Document; Regulatory Criteria Document for the Disposal of Defense Transuranic Mixed Waste in a Geologic Repository; the 1991 No-Migration Determination Annual Report to EPA; EPA comments on the 1991 Annual Report; the 1992 No-Migration Determinations Annual Report to EPA; and EEG comments on SAND91-0893.

A one-day tour of the WIPP site was conducted early in the review process to acquaint the PART members with the specifics of the site. The full-day tour was conducted by Tom Schultheis (SNL) and Ken Aragon (WID). The underground portion of the tour included Panel 1, Room Q, Room H, Site and Preliminary Design Validation (SPDV), as well as the Construction and Salt Handling and the Waste shaft areas. The surface tour concentrated on the Waste Handling Building, particularly the CH bay. The tour concluded with a question and answer session with Tom Schultheis.

1.4.3.1 PART Meetings and Interviews

After an initial meeting in Germantown, Maryland (December 11, 1992), the PART members studied review material made available to them and began a series of interview meetings following the tour of the WIPP facility. The purpose of these interviews was to gather additional information not available in the base documentation listed above and other references. PART interviews were coordinated by the PART Chairperson with WPIO, WPSO, SNL, WID and EEG and included interviews with the WPIO Technical Support Group (TSG), the WID compliance staff, the SNL PA staff and principal investigators, as well as the EEG staff.

The first PART meeting was held on January 15, 1993, following the WIPP site tour on January 14, 1993. PART members met with John Arthur, Mark Matthews, and Pat Higgins of WPIO, as well as members of the WPIO TSG, who discussed current and planned activities with regard to PA. A considerable amount of time was spent discussing a QA database for critical PA parameters. The second PART meeting was held on February 4-5, 1993, in Albuquerque, New Mexico. The purpose of the meeting was to conduct interviews with the SNL PA staff. In addition to Rip Anderson, PART interviewed Mel Marietta, Fred Mendenhall, Rick Beauheim, Joe Tillerson, Palmer Vaughn and Jon Helton. On March 11-12, 1993, the PART again met in Albuquerque, New Mexico, this time to interview the WID compliance staff and the SNL principal investigators. The PART had discussions with Bob Kehrman, Rohit Jain and Elaine Gorham.

The next meeting of PART was in Seattle, Washington, on April 5-6, 1993, at the office of Golder Associates, Inc. PART was briefed by Lokesh Chaturvedi and William Lee of the EEG on EEG's concerns regarding WIPP PA testing activities. Major concerns expressed by the EEG were related to scenario definition, solicitation of expert judgment for the rate of inadvertent human intrusion, gas generation and fracturing, the use of data versus judgment, the lack of information on source terms, and the incomplete documentation of computer codes.

In May, PART held two meetings: one in Germantown, Maryland, on May 6-7, 1993, and one in Albuquerque, New Mexico, on May 27, 1993. The meeting on May 6-7, 1993, was to update Mark Frei and Steve Schneider on the status of PART activities. The meeting on May 27, 1993, was an interview with Dori Ellis and Wendell Weart to discuss SNL management's role in PA decision making. Additional meetings were held by the PART in June in Seattle, Washington, and conference calls were conducted in July and August to discuss report preparation.

As noted in Subsection 1.3, the PART has identified a subset of the integrated requirements from the draft RCD (DOE, 1992) as a partial basis for evaluation of the WIPP PA program. This subset and the relationship to the RCD requirements are given in Appendix A. These requirements are summarized in this subsection; they provide the basis for the development of the partial issue tree and the conceptual model because the objectives of modeling/analysis should drive the needs of the conceptual and numerical modeling and other analysis efforts (Simmons and Cole, 1985).

Summarizing from the specific draft RCD requirements that form part of the basis for this review, the SNL PA staff (WID compliance staff) [a] must undertake two major efforts.

1.0 The staff must evaluate compliance of the total WIPP geologic disposal system with the regulations of 40 CFR 191 Subpart B *(40 CFR 268.6)* through the use of compliance analyses consisting of both quantitative PA modeling and qualitative analyses. The modeling and analyses shall consider the likelihood and consequences of natural processes and events that may disturb the disposal system (PC1.004, PC1.012, and PC1.014 a) from the time of emplacement of the wastes. The likelihood and consequences of human intrusion will also be evaluated through the use of compliance analyses consisting of both quantitative PA modeling and qualitative analyses. Additionally, an evaluation to determine whether there are special sources of groundwater within or less than 5 km (3 mi) beyond the controlled area (the dashed boundary line in Figure 1-13) must also be conducted (PC2.001 a-b).

1.1 These evaluations and compliance analyses must consider the contributions of all components of the geologic disposal system (i.e., the natural and engineered barriers as well as the radionuclide and hazardous constituent content and characteristics of the emplaced waste), except those components that can be demonstrated to make a negligible contribution (PC1.009 a-b, and PC1.008 a). This evaluation must also demonstrate the disposal system's ability to control, minimize, or eliminate waste release (PC1.008 b) for the likely natural processes and events; others can be ignored (PC1.0013 a-e). Likely processes and events are those having an estimated probability of occurrence greater than 1 in 10,000 over 10,000 years.

1.2 The evaluations and analyses must address all pathways for release (groundwater, surface water, soil, and air) at the boundary of the control area (at the top and bottom of the disposal unit boundary or its lateral extent as defined by the intersection with the vertical boundary of the control area) as illustrated in Figure 1-13 (PC1.003 a-b, PC2.001 a, and PC2.002 a-e).

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[a] In general, there is little difference in the RCD requirements for the WID compliance staff and the SNL PA staff. However, when they are different, the requirements for the WID compliance have been placed in parentheses and italicized.

1.3 The compliance analyses and evaluations must be supported by laboratory and field studies, as well as by expert judgment (PC1.003 a-b and PC1.004).

1.4 The models used in the SNL compliance analyses for 40 CFR 191 Subpart B and the WID compliance analyses 40 CFR 268.6 must have the following attributes:

  1.4.1 These models must use identical physical descriptions of the disposal system (PC1.019);

  1.4.2 The pathways considered by these models must be consistent (PC1.011);

  1.4.3 These compliance analyses must use comparable conceptual models as the basis for their mathematical and computational models (PC1.020);

  1.4.4 These models must simulate the expected behavior of the disposal system (PC1.018) and predict any resulting releases of hazardous or radioactive constituents from the time of waste emplacement until 10,000 years following closure (PC1.021 a);

  1.4.5 These compliance models must be evaluated (PC1.025).

1.5. Specific engineered barrier system design and evaluation constraints and the requirements important to these compliance analyses include the following:

  1.5.1 The design must be physically and chemically compatible with the natural barrier system (PC6.001 a-b); and

  1.5.2 Design of engineered barriers, as well as the analyses that assess their adequacy, must be supported by analytical data (PC6.002 a-c).

1.6. An assessment must be carried out with these compliance models that excludes consideration of water wells within the controlled area and that estimates the annual dose equivalent from the undisturbed disposal system to any member of the public for 1,000 years after disposal (PC1.024 a-b-c).

1.7. An evaluation of the likelihood and consequences of human intrusion must be carried out with these compliance models under the following constraints:

  1.7.1 The likelihood of human intrusion must consider the controls imposed to make *it less likely, and furthermore, the evaluation of likelihood will be primarily* based on the effectiveness of these primary markers (PC1.015 a-d); and

  1.7.2 In evaluating the consequences of human intrusion, only single isolated one-time intruder events that are no more severe than inadvertent and intermittent human intrusion by exploratory drilling for resources (other than the waste) will be considered. It must be assumed that systematic or persistent exploration within the controlled area does not occur (PC1.016 a-d).

1.8. Sensitivity and uncertainty analysis of the compliance modeling must be performed that includes the following:

  1.8.1 the uncertainty in processes and events (PC1.027 a);

  1.8.2 the likelihood and consequences of alternative conceptual models (PC1.027 b);

  1.8.3 representation of model parameters (PC1.027 c);

  1.8.4 sensitivity studies of the models (PC1.027 d); and

  1.8.5 an assessment of the accuracy of the model that includes model verification results (PC1.027 e).

2.0 The staff must develop a demonstration based on these compliance analyses (1.0 above) and document the basis for this demonstration (PC1.005 and PC1.006).

2.1. This demonstration must establish whether there is a reasonable expectation that the WIPP geologic disposal system will comply with the quantitative radionuclide limits specified in 40 CFR 191 Subpart B *(the quantitative health based hazardous constituents limits of 40 CFR 268.6)* for all the expected processes and events (PC1.002 a-b, PC1.013 c, PC1.014 b, and PC1.021 b-c). Further specifics for this demonstration include the following:

2.1.1 This demonstration must be routinely updated (along with the PA modeling and analyses) with the latest new and relevant information until the time of repository closure (PC1.007);

2.1.2 In this demonstration the PA results for 40 CFR 191 Subpart B §191.13 compliance comparisons must be presented as a single complementary cumulative distribution function (CCDF) that indicates the probability of exceeding the cumulative release standard (PC1.022 a-b);

2.1.3 The demonstration must show that waste migration prediction models were calibrated to specific site conditions, physical features, and emplaced wastes (PC1.026 c);

2.1.4 The demonstration must show that modeling results are consistent with actual field measurements and representative of the actual physical system (PC1.026 d).

2.2. General requirements are that the documentation must include discussions of the records of quantitative and qualitative evidence used to develop the PA models as well as any supplementary information such as natural analogs, evidence that supports the process models, parameter ranges, geometric conceptual models, hypotheses, and any simplifying assumptions used (PC1.006). Specifics for this documentation are as follows.

2.2.1 The documentation must describe boundaries of the control area and disposal unit (PC2.001 b).

2.2.2 The documentation must include discussions regarding the consequences of the human intrusion events evaluated and a description of these analyses (PC1.016 d).

2.2.3 The documentation must include justification for the selection or generation of the single CCDF for comparison with 40 CFR 191 Subpart B standards (PC1.023).

2.2.4 The compliance models and their evaluation must be documented (PC1.025).

2.2.5 The documentation must present discussions of the model results, including:

2.2.5.1 simplifying assumptions in the conceptual, mathematical, and computational models (PC1.026a);

2.2.5.2 rationale for selection of the waste components modeled (PC1.026 b);

2.2.5.3 calibration of waste migration prediction models (see 1.1.4 above) and the comparisons that show modeling results are consistent with actual field measurements and the comparisons that show that the models are representative of the actual physical system based on the consistency of model results with the actual field measurements (PC1.026 c-d); and

2.2.5.4 comparison of model results with observations and an explanation of any differences (PC1.026 e).

2.2.6 The documentation must include a comprehensive, detailed description of the natural system. This documentation of the natural system must describe the geology as well as the surface and groundwater hydrology of the repository site and setting (PC4.001 b), and must also provide an analysis of the geochemistry of the system relevant to waste migration and including a characterization of the rock, soil, air, and water chemistry (PC4.001 a).

1.4.4 PART Report Development and Preparation

Reviews of the base set of documents (Subsection 1.4.3) and other requested reference material, along with participation in interviews, and discussions among the PART members themselves, formed the basis for their evaluations of the technical adequacy of the WIPP PA program and the formulation of their recommendations for program changes. PART members did not necessarily perform a complete review of the base set of documents or the supplementary documentation requested during the course of the review. The members were free to select the scope and depth of review performed on each document. In general, each member conducted a review within his or her own area of expertise.

The predecisional draft report was issued to PART members only. Members had the opportunity to comment on the entire report and the Chairperson attempted to resolve any conflicts among PART members. The findings in the report reflect the consensus of the PART. Conflicts not satisfactorily resolved were documented as an appendix to the main report and provided to the EM-342 Director. Once the final draft report was accepted by PART, it was concurrently issued to the EM-342 Director, WPIO, WPSO, WID, and SNL for review and comment. After the comments were resolved, the final report was signed by PART members and sent to the Director, EM-342. Receipt of the final report by the EM-342 Director completed the PA independent review.

1.4 VERIFICATION CALCULATIONS

This portion of the review involves the performance of independent PA calculations to verify and perform sensitivity assessments for the calculations done by SNL. This work is ongoing, and will be published separately at a later date.

The work uses Golder Associates' Repository Integration Program (RIP) PA model, which is a high-level model designed for rapid, simplified PA calculations. The work is being conducted in two phases: (1) the verification phase, in which RIP is used with the same conceptual models and data sets as SNL's published studies, in order to verify the SNL results, and (2) the sensitivity phase, in which RIP is used with alternative conceptual models developed by the review team, in order to evaluate their potential significance for repository safety. It is expected that the significance of alternative potential pathways, and of alternative modeling of disruptive events, will be key areas to be investigated.

1.5 TOPICS EXCLUDED BY PART

As outlined in the Performance Assessment Independent Review Management Plan, PART focused on a review of those PA activities which were directly related to a determination of compliance with the applicable regulations. However, certain aspects of the PA program were, or are, being reviewed by other organizations within DOE which have those functional authorities. For example, PART did not review the validity of data or the data collection techniques or the quality control of the data. This activity was part of a separate review being conducted jointly by WPIO and EM-342. The PART assumed that all data presented in the SNL reports were accurate.

The PART also restricted its review to the priorities assigned to PA activities. Activities associated with repository operation, environmental safety and health, safeguards and security, and budget and scheduling were specifically excluded from the review. However, PART did investigate how decisions were made and schedules were developed in support of PA .

The PART concentrated on PA activities for the demonstration of compliance with the long-term disposal standards contained in 40 CFR 191 Subparts B and C (proposed) and 40 CFR 268.6. This review specifically excluded those activities and regulations that would apply to the operation of the facility for the disposal phase.

2.0 PERFORMANCE ASSESSMENT METHODOLOGY

This section summarizes the approaches being taken by WIPP, through Sandia National Laboratories and Westinghouse Waste Isolation Division, to address the long-term performance standards in 40 CFR Part 191 Subpart B and 40 CFR Part 268.6, respectively. It is these regulations which determine the PA methodology to be used. Subsection 2.1 describes the requirements of 40 CFR Part 191 Subpart B in detail. Subsection 2.2 discusses the SNL approach to addressing the requirements of §191.12(q) (quantitative PA modeling) and §191.13(a) (probabilistic assessment of cumulative releases). This discussion includes a description of the scenarios, including the scenario selection and evaluation process, the performance measure, the modeling approach, and the sensitivity and uncertainty analyses. The subsection concludes with a brief discussion of the application of the probabilistic approach and the complementary cumulative distribution function (CCDF). Following the same format as Subsection 2.2, Subsection 2.3 considers the WID approach to addressing the requirements of 40 CFR Part 268.6, looking at scenarios, performance measure, modeling approach, sensitivity and uncertainty analysis, and probabilistic approach and the CCDF. The WID approach is different from that of SNL because the long-term performance standards of 40 CFR 268.6 are not as detailed or prescriptive from a methodological standpoint as those of 40 CFR 191, Subpart B.

2.1 40 CFR PART 191 SUBPART B

The provisions of 40 CFR Part 191 Subpart B state that the repository must meet certain performance standards in order to be licensed. These regulations mandate a quantitative assessment of the performance of the disposal system, and describe specific performance measures in terms of

1) radioactive material releases to the accessible environment (§141.13),
2) radiation doses received by the public (§191.14), and
3) radioactive contamination of certain sources of groundwater in the vicinity of the disposal system (§191.16).

The performance measures for the containment requirement are, as stated in §191.13(a), 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 ten 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)."

Table 1 in Appendix A of 40 CFR 191 gives limits for cumulative releases over 10,000 years for twelve specific radionuclides and any other alpha-emitting or non-alpha-emitting radionuclide (with a half-life of over twenty years) in curies per unit of waste. The estimated cumulative release for a particular radionuclide is divided by the corresponding limit in Table 1 to produce a normalized cumulative release. If the ratio is less than one, then compliance is determined for both requirements (1) and (2). If more than one radionuclide is present in the disposal system, then the sum of the ratios for the individual radionuclides should be less than one to demonstrate compliance for both requirements (1) and (2).

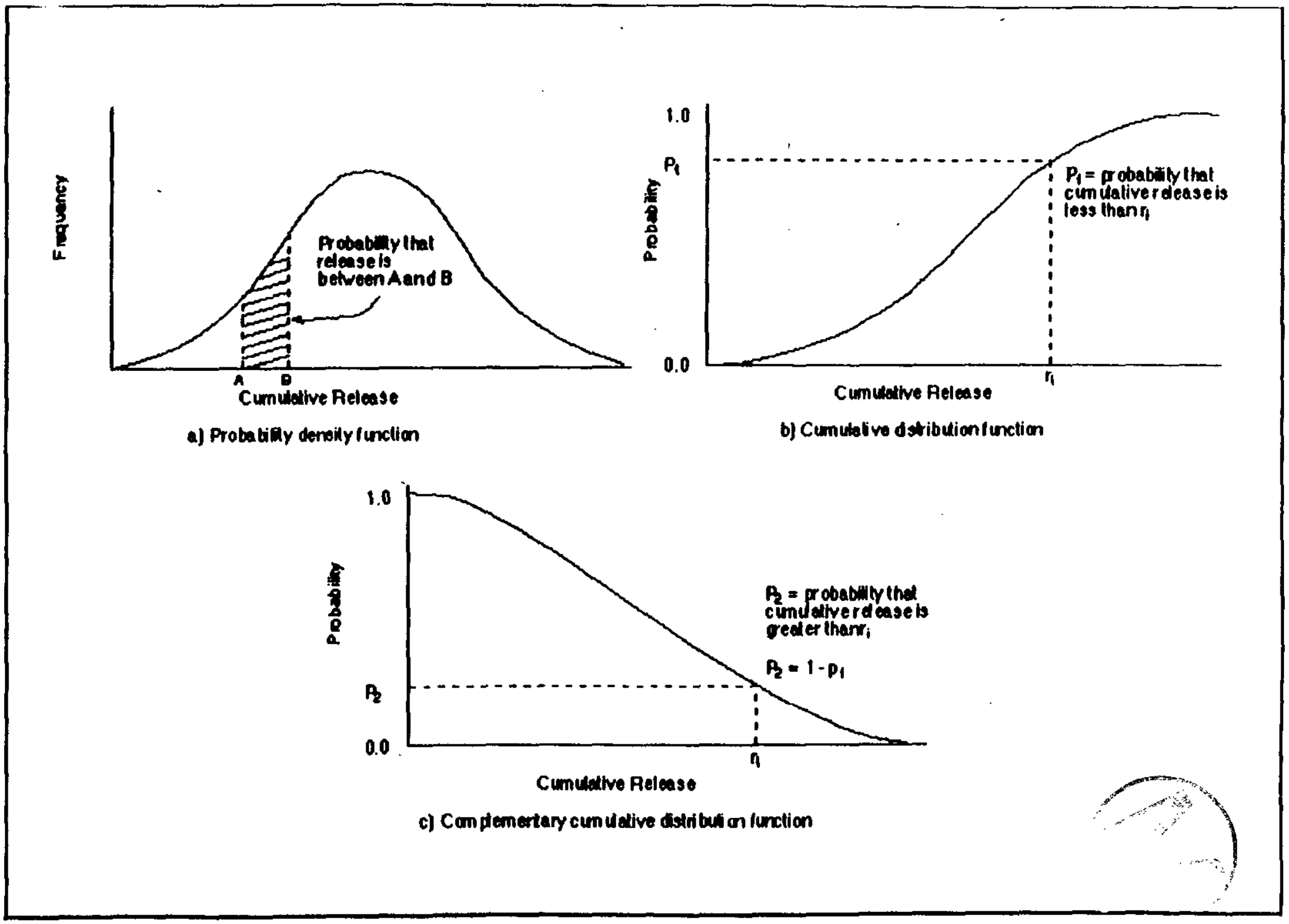
The quantitative standards of §191.13(a) are stated in terms of likelihoods (i.e., probabilities) because it is recognized that there are uncertainties in the predictions of cumulative releases over 10,000 years. The uncertainty in the cumulative release prediction can be expressed by presenting the result in terms of a probability density function (PDF), illustrated in **Figure 2-1a**. This is simply a plot of the probability of the various possible cumulative release results. Hence, to obtain the probability of the result falling between the value A and the value B (see figure), one need only to integrate under the PDF between these two values.

An alternative manner of presenting the same information is the cumulative distribution function (CDF). This is developed by integrating over the entire PDF, and is illustrated in **Figure 2-1b.** By definition, integrating over the PDF from the lower limit of its range to the upper limit of its range yields a value of 1.0, and the CDF therefore ranges from 0.0 to 1.0. As shown in the figure, a particular point (e.g., $[r_i, p_1]$) on the CDF is interpreted as follows: p_1 is equal to the probability that the result (the cumulative release) is *less* than or equal to r_i.

A third way of presenting this information is the complementary cumulative distribution function (CCDF). The CCDF is illustrated schematically in **Figure 2-1c**. As shown in the figure, a particular point (e.g., $[r_i p_2]$) on the CCDF is interpreted as follows: p_2 is equal to the probability that the result (the cumulative release) is *greater* than r_i (i.e., p_2 is equal to the probability of exceeding r_i). As indicated by its name, the CCDF is the complement of the CDF. That is, $p_2 = 1-p_1$. Note that the containment requirements of §191.13(a) are stated in terms of complementary cumulative probabilities (i.e., probabilities of exceedence). Therefore, release predictions can be directly compared to the standard if they are presented in terms of a CCDF. Because the two complementary cumulative probabilities of §191.13(a) differ by two orders of magnitude (0.1 and 0.001), it is most effective to present the CCDF on a log-log scale. In such a plot, the horizontal axis represents the logarithm of the normalized release over 10,000 years, and the vertical axis represents the logarithm of the probability of the magnitude of such a release. **Figure 2-2** shows an example of a log-log CCDF with the 191.13(a) containment standards superimposed. In this particular example, the predicted release does not exceed the standards.

If the repository is simulated in terms of various mutually-exclusive scenarios (each of which is described by disjoint subsets of uncertain parameters), a separate CCDF will be produced for each scenario. In order to compare such results to the containment standards, it is necessary to combine the results of the scenarios in an appropriate manner. This is accomplished by multiplying the probability axis of each curve by a weighting factor and adding them together. The weighting factor for each curve is simply the probability of that particular scenario. (The total "weight" for all scenarios must add to one.) An example of how CCDFs for two scenarios (having probabilities of 0.99 and 0.01) are combined is shown in **Figure 2-3.** The character of this combined CCDF is representative of results of the analysis in Sandia PA documents.

The process of developing a CCDF appears to be objective and straight-forward. However, uncertainties in the development of the conceptual model of the components of the repository system and assumptions required for mathematical modeling are difficult to capture in the CCDF. For example, unless all components of a repository system are represented in the numerical model, the



a) Probability density function

b) Cumulative distribution function

c) Complementary cumulative distribution function

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Figure 2-1. Presentation of Probabilistic Results.

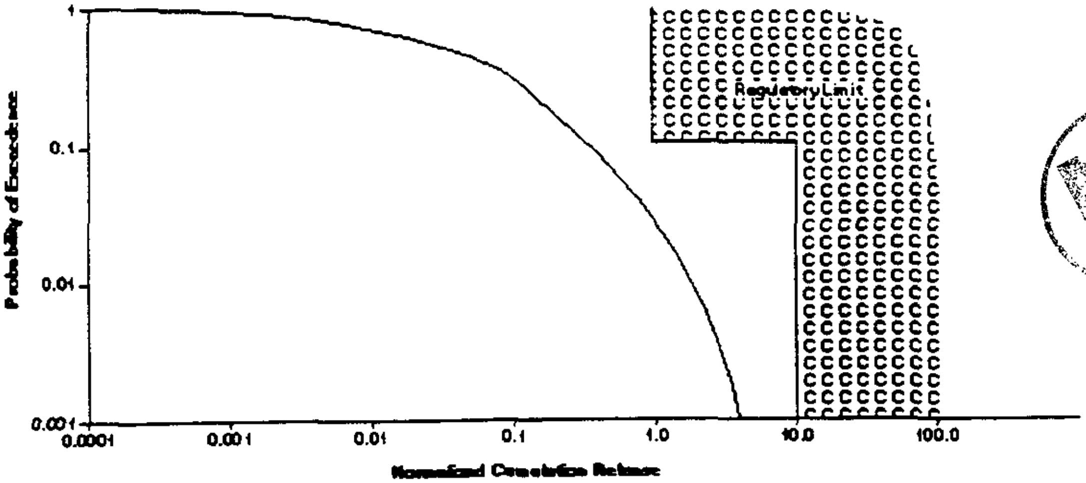


Figure 2-2. Log Log CCDF For Cumulative Release.

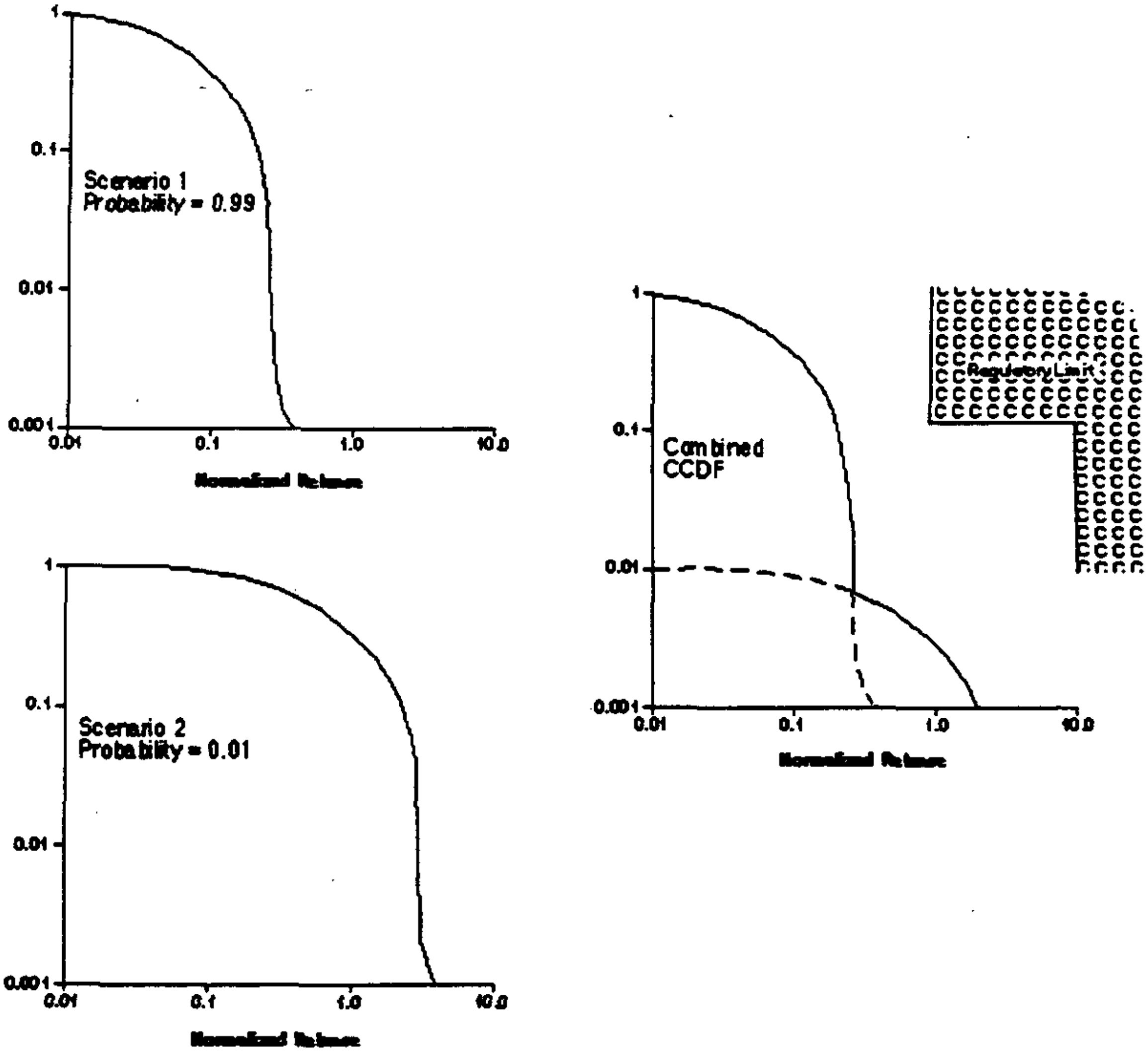


Figure 2-3. Combining CCDFs.

results in terms of a calculated CCDF do not describe the true uncertainty in cumulative release. This issue is discussed in more detail in Subsection 2.2.4. The acknowledgment of remaining uncertainty is further developed in §191.13(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 (emphasis added) on the basis of the record before the implementing agency, that compliance with §191.13(a) will be achieved."

It is the role of DOE to decide when the description of the current state of the repository system is sufficiently detailed and when the processes potentially acting upon it are sufficiently understood that the likely performance of the repository can be estimated. The other sections of this report address the sufficiency issue of whether the record being developed that includes PA will be able to satisfy the "reasonable expectation" requirement.

The provisions of §191.14 require active institutional controls for 100 years after closure, monitoring for the period of active institutional control, and the use of engineered, as well as natural, barriers to contain the waste. It also states that areas that have experienced mining for resources should be avoided as locations of a repository, "unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future." Impacts of resource extraction will be discussed in Subsection 3.2.2.2.

The provisions of §191.15 mandate specific quantitative limits for annual exposures (25 millirem whole body and 75 millirem to any critical organ) to the public up to 1,000 years after disposal, assuming undisturbed performance of the repository. All exposure pathways have to be considered, but this article specifically requires that the drinking water pathway be analyzed assuming 2 liters/day from any significant source of ground-water outside the controlled area surrounding the repository. These requirements are not stated in probabilistic terms, and therefore, presumably do not require the calculation of a CCDF.

The groundwater protection requirements of §191.16 set quantitative limits on the permissible concentrations of specific radionuclides and a cap on the annual dose equivalent from all radionuclides combined to 4 millirem from 2 liters/day consumption of groundwater.

2.2 SNL APPROACH FOR 40 CFR PART 191 SUBPART B

The SNL PA approach is being developed within the requirements of §191.12(q) (quantitative PA modeling) and §191.13(a) (probabilistic assessment of cumulative releases). The major steps in the PA process, as defined in Marietta et al. (1989), are the following:

1) characterize disposal system and site;
2) develop scenario;
3) analyze scenario consequences;
4) perform sensitivity and uncertainty analyses; and
5) assess compliance with regulations.

Each of these five steps represents many activities, in which there are major feedback loops and interconnections. The following discussion of the SNL PA approach will touch briefly on the following issues, which are subsets of the five steps listed above:

- General description of conceptual model and scenarios (Steps 1 and 2);
- Performance measure (Step 3);
- Modeling approach (Step 3);
- Uncertainty and sensitivity analyses (Step 4); and
- Probabilistic approach and CCDF (Step 5).

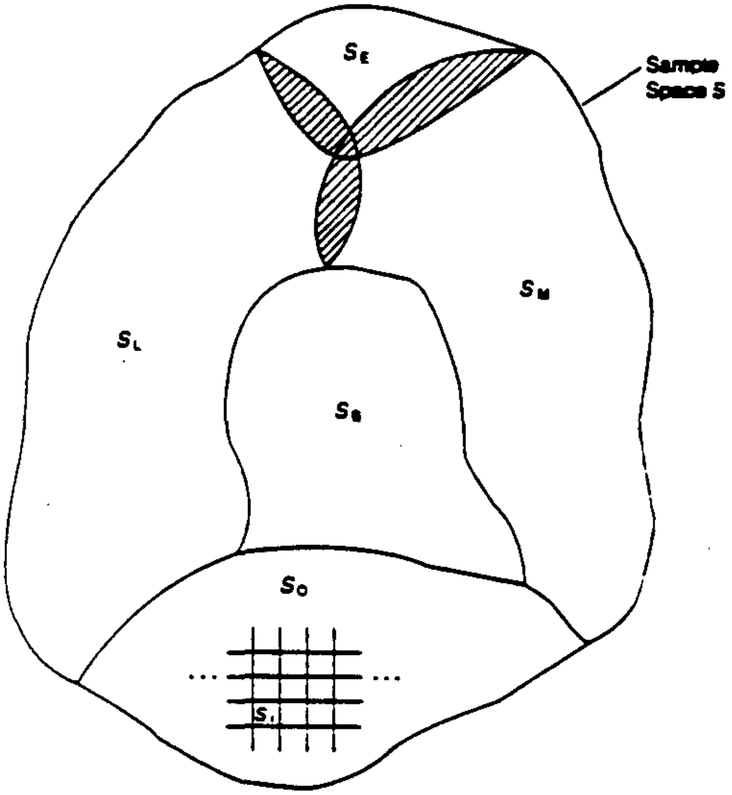
The SNL approach for addressing the requirements of 40 CFR191 Subpart B has been to develop most of the needed computer codes in house. However, the availability of documentation on these codes has lagged behind the reporting of the results of analyses in the annual performance assessment summaries. The lack of formal documentation can be problematic from a compliance standpoint because the codes will not be familiar to regulators, nor will they have undergone independent peer review. This lack of formal documentation may make it more difficult to demonstrate a reasonable expectation of compliance.

2.2.1 General Description of Scenarios

In order to demonstrate compliance with the performance requirements of 40 CFR 191, the DOE must consider the undisturbed performance and the possible events that may disrupt the repository system (§191.12(p)). Undisturbed performance refers to the behavior of the repository system assuming natural structural, hydrogeologic and chemical processes. The conceptual model for the WIPP repository system includes salt creep; brine inflow; gas generation from anoxic corrosion, microbial action, and radiolysis; brine and gas outflow into interbeds in the Salado Formation and also to the accessible aquifer (the Culebra Dolomite Member of the Rustler Formation) above the Salado Formation by way of backfilled and sealed shifts; and engineered barriers.

The WIPP Performance Assessment Department used a scenario selection and evaluation process similar to that described in Cranwell et al. (1982a and reissued in 1990), which systematically defines the events and processes that could affect the integrity of the repository system, evaluates the probability of an event occurring, and assesses its potential for leading to a release of radioactive constituents to the accessible environment. The methodology is described conceptually in **Figure 2-4**. The sample space S represents all possible 10,000-year time histories of the disposal system at the WIPP. The scenarios are screened on the basis of the likelihood of their occurrence and their potential consequence. Subset S_B contains all time histories that fall within the bounds of reasonably anticipated occurrences of natural processes (greater than 1 in 10,000 in 10,000 years) acting on the disposal system over 10,000 years, which represent undisturbed performance. Subsets S_M, S_L, and S_E are associated with disruptive events, such as volcanism. Subset S_M contains time histories that include disruptive events that may occur with probability greater than 1 in 10,000 in 10,000 years, but the consequences do not compromise repository performance. Subset S_L represents time histories that can be reasonably screened out of consideration because they include disruptive events that are of sufficiently low probability of occurrence (less than 1 in 10,000 in

10,000 years). Time histories that can be excluded by regulatory criteria are contained in subset S_E. These three subsets are not mutually exclusive, and the shaded area represents the overlap. Finally, Subset S_O contains all of the time histories that include disruptive events that are left after the scenario screening process. The S_i in the cross-hatched area within S_O represents sets of parameters which give rise to specific time histories containing disruptive events that can significantly affect repository performance.



S_B = anticipated base case
S_M = disruptive events, little consequence
S_L = low probability events
S_E = excluded by regulatory criteria
S_O = remainder

Figure 2-4. Conceptual Description of the SNL Scenario Selection Process.

According to the methodology, subsets of the time histories that have to be analyzed by performance assessment are the ones that fall within subsets S_B, S_O, or S_M. In practice, the methodology is not followed rigorously, because it is not possible to enumerate and evaluate all possible time histories of all possible combinations of natural processes, subjected to all possible sequences of disruptive events that can significantly compromise repository performance. Guzowski (1990) amended the methodology to make use of earlier scenario analyses efforts to develop a set of scenarios for WIPP that is more practical to evaluate.

The amended scenario selection process screened some 49 natural and human-induced events and processes. Seven of the processes—erosion, sedimentation, climate change, seismic activity, Rustler-Salado contact dissolution, shaft and borehole seal degradation, excavation-induced fractures, and gas generation (WIPP PA 1992, Volume 2, Table 4.2)—are expected to occur over the 10,000 years. Therefore, these processes are considered non-disruptive and have been retained for the undisturbed case, Subset S_B, also called the base case.

For analysis purposes, the base case subset (S_B) and the subset containing disruptive events of no consequences (S_M) are considered to consist entirely of no-release scenarios over the 10,000-year simulation period. Subset S_L, containing events considered to be not credible by the WIPP performance assessment staff (e.g., tectonic activities) are excluded from consideration due to low probabilities. Since subset S_E is excluded based on regulatory considerations, only subset S_O remains to be considered for analysis. That is, only time histories resulting from parameter sets within S_O are assumed to result in any kind of release.

Within S_O, a set of mutually-exclusive scenarios was defined (starting with the base case) based on a logic-diagram type of analysis that developed sequences of disruptive events that could potentially lead to the escape of radionuclides from the repository and migration to the accessible environment. The mutually-exclusive scenarios resulting from this process are defined by their different model and code configuration requirements for the performance assessment analysis.

According to the scenario selection process described in Guzowski and Helton (1991), three possible types of events that may disrupt the repository stem from human intrusive activity; they are:

- potash mining in the WIPP vicinity and associated surface subsidence,
- one or more boreholes passing through a waste panel and penetrating a brine pocket, and
- one or more boreholes passing through a waste panel without penetrating a brine pocket.

The 1992 PA, Volume 1, lists seven scenarios representing all possible combinations of these three events and a base case, which corresponds to undisturbed performance, that are to be carried forward for the performance assessment.

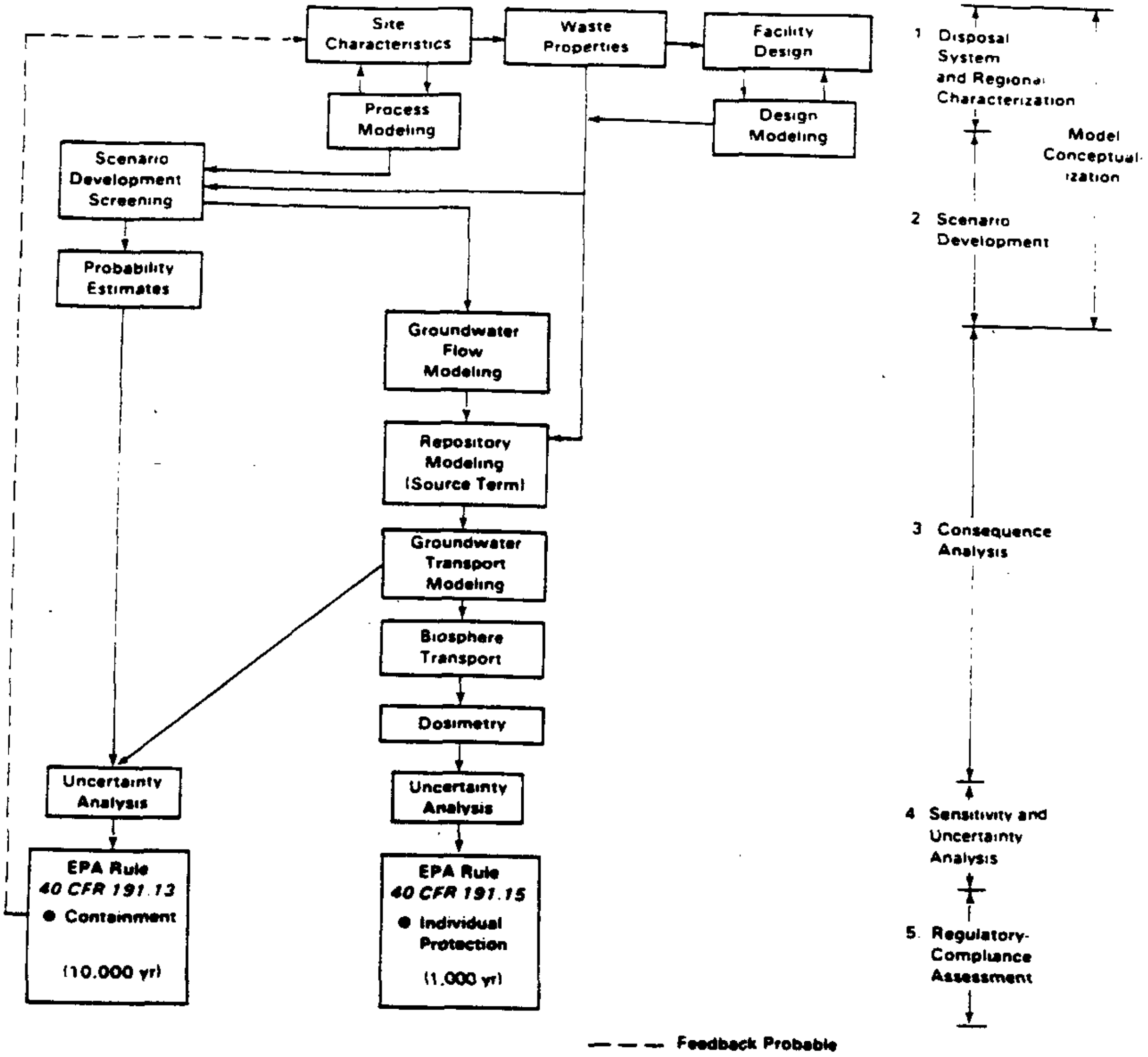
2.2.2 Performance Measure

Most of the performance assessment effort to date has gone into assessing whether the WIPP repository performance will comply with the containment requirements of §191.13(a). Therefore, the measure that the performance assessments concentrate on is the normalized release of radionuclides to the accessible environment. The analyses used to assess this performance measure provide the necessary intermediate calculations to address the individual and groundwater protection performance measures of §191.15 and §191.16, respectively.

Part of the rationale given for not conducting analyses to address §191.15 and §191.16 is that, according to the results of the performance assessment modeling for the undisturbed or base case, there are no releases to the biosphere. However, since the modeling done to date assumes perfect seal performance, the conclusion that there are no releases to the biosphere in the undisturbed case is suspect. Performance assessments done to date do not specifically address individual and groundwater protection requirements.

2.2.3 Modeling Approach

The WIPP Performance Assessment Department developed an assessment logic and structure, shown in **Figure 2-5** (Figure 2-5 of Marietta et al., 1989) that describes the assumed physical and environmental processes and disruptive events that must be considered in order to address the



TRI-6342-16-0

Figure 2-5. Compliance Assessment Methodology Structure (modified from Rechard, 1989).

compliance requirements of §191.13(a). The figure shows that, at the present time, the performance assessments are focused on the containment requirements (§191.13), and that the individual protection requirements (§191.15), which require biosphere transport and human dose modeling, are being deferred to a later time. The figure also shows the iterative nature of the PA process; however, discussions with principal investigators suggest that the feedback is not as extensive as implied by the figure. This is discussed in more detail in Section 8.

The execution of even a single PA analysis for a single scenario requires the assimilation of qualitative and quantitative information and the sequential calculation of many different interim quantities. The WIPP Performance Assessment Department has developed a computer system to manage the flow of information throughout the PA and to provide a structure to maintain quality assurance records. An overview schematic diagram that shows the sequence of calculations and the flow of information through a PA analysis is provided in **Figure 2-6** (Figure 2-8 in Marietta et al., 1989). This figure shows the complexity of the information needs and calculations required to demonstrate compliance with §191.13.

The modules that are used by the PA systems include finite element, finite difference and analytical model codes. The models used in the 1992 PA analyses and their functions are listed in **Table 2-1**. The constitutive relationships and input parameter requirements of these models for simulating the described processes is discussed in the other sections. **Figure 2-7** (Figure 1-1, Volume 2, of the 1992 PA analyses) shows the flow of information among the models described in the 1992 PA analyses. Not all of the system is automated since GRASP-INV, SANCHO, and CUTTINGS are run outside the CAMCON system, and manual data transfers are used for the analyses.

Table 2-1. Computer Codes Used in the 1992 WIPP Performance Assessment (after Table 3-1 in Volume 2 of 1992 PA)

CODES	FUNCTION
BRAGFLO	Multiphase flow of gas and brine through porous heterogeneous reservoir
CCDFPERM	Probabilities for human intrusion drilling
CUTTINGS	Quantity of radioactive material brought to surface in cuttings and cavings generated by drilling
GRASP-INV	Simulation of transmissivity fields calibrated from measurements and pressure fields
PANEL	Rate of, and cumulative discharge of radionuclides from repository panel through an intrusion borehole
SANCHO	Porosity of waste as function of time and moles of gas generated
SECO2D	Single-phase Darcy flow for ground water in two dimensions
SECOTP	Fluid flow and transport of radionuclides in fractured porous media

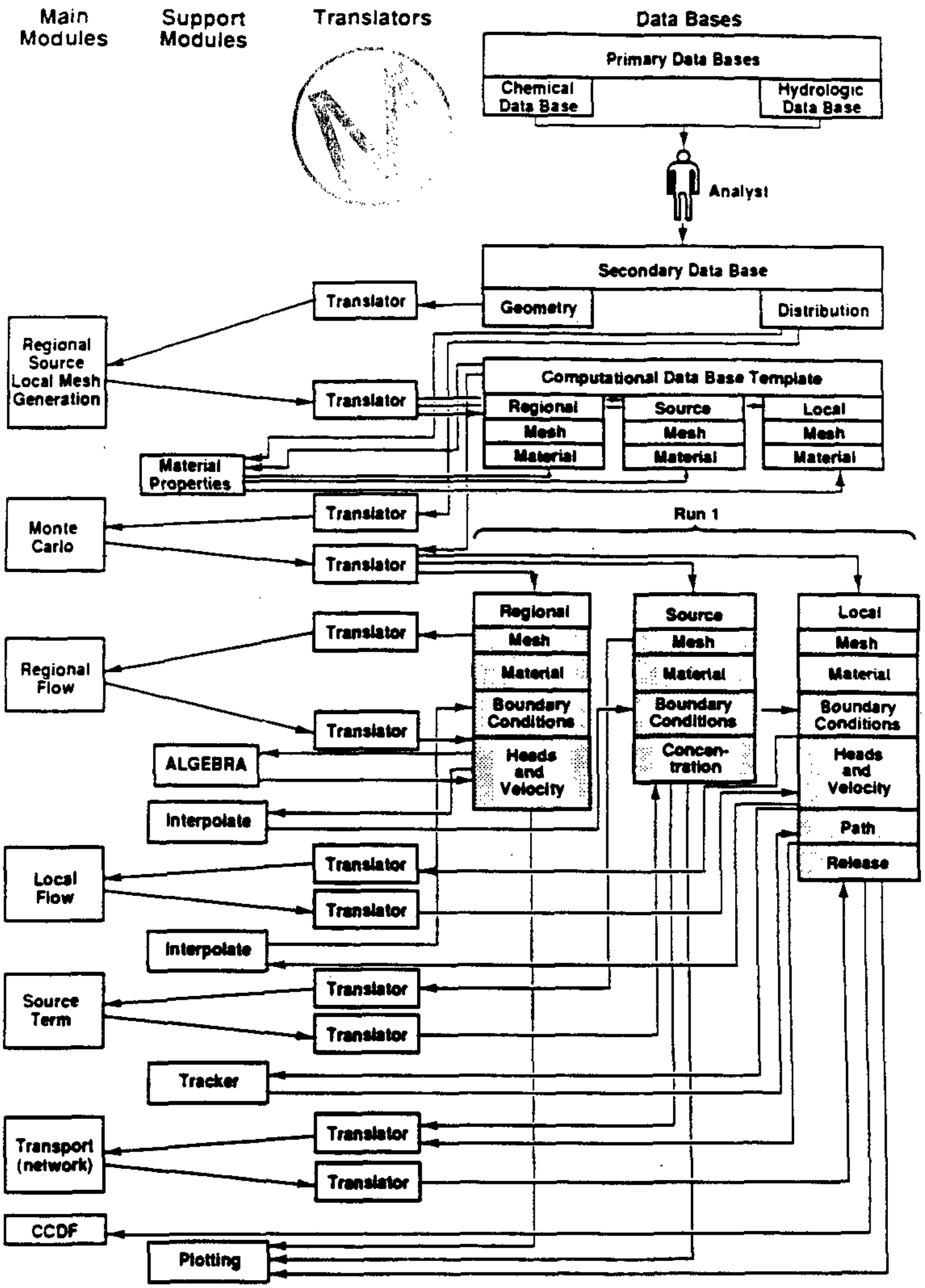


Figure 2-6. **Algorithm for Logical Data Flow During Compliance Assessment (Rechard, 1989).**

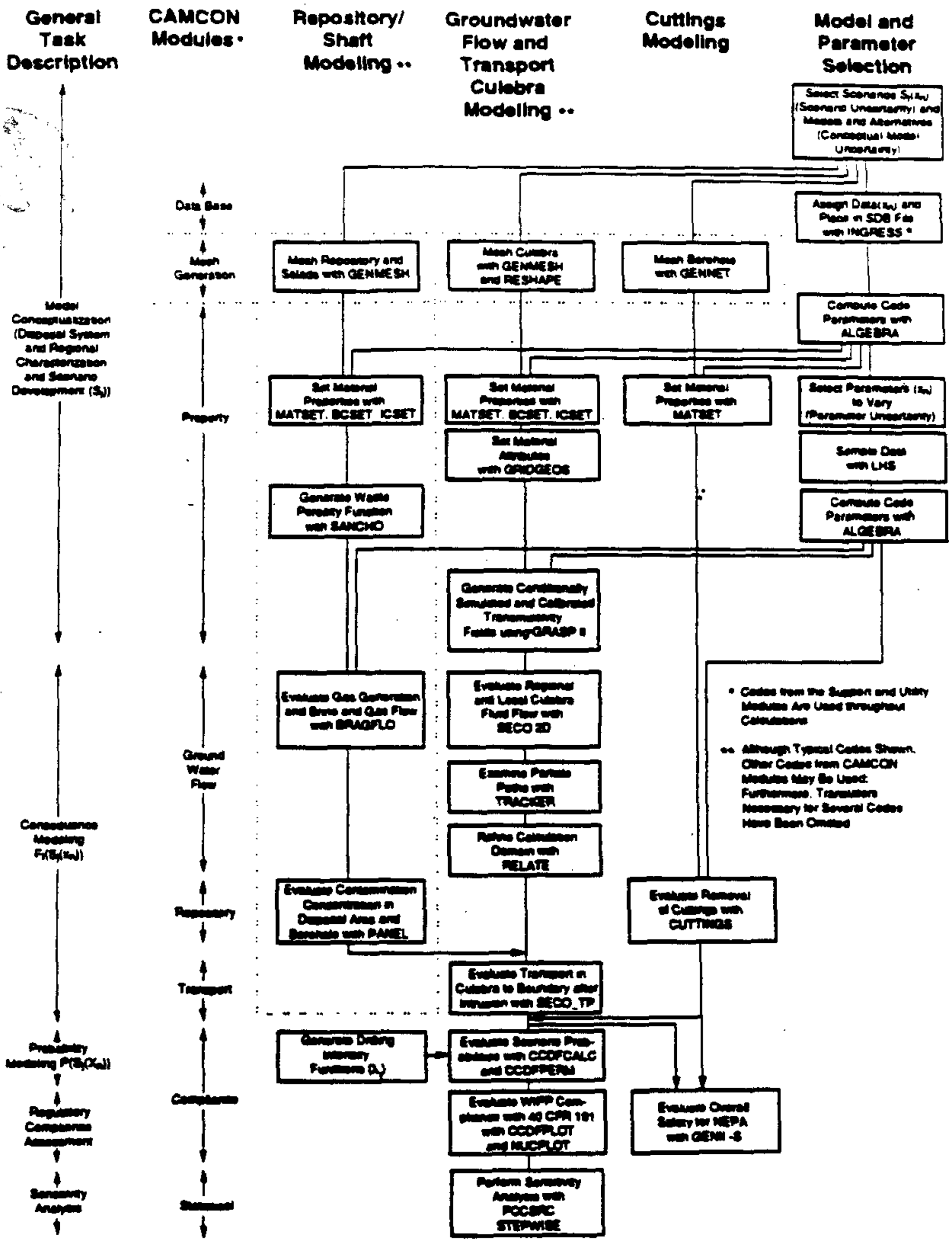


Figure 2-7. **1992 Organization of Programs in CAMCON (after Rechard, 1992).**

2.2.4 Sensitivity and Uncertainty Analyses

The probabilistic nature of the containment performance standard detailed in §191.13 requires that a quantitative estimate be made of the uncertainty in the value of the performance measure in order to assess the probability of exceeding the standard. Because of the complexity of the models, the sequential nature of the calculation and the number of input parameters involved, error propagation methods of estimating uncertainty are not appropriate. The uncertainty analysis approach used by the WIPP Performance Assessment Department is Monte Carlo simulation (Marietta et al., 1989).

In a Monte Carlo simulation, the values of the input parameters are assumed to be uncertain. These parameters are therefore represented using probability distributions which are sampled to produce an empirical probability distribution (and a CCDF) of the values of the output performance measure. The Monte Carlo approach to uncertainty analysis, although it directly leads to the desired CCDF, can be computationally intensive if the number of input parameters is large and the models are complex. This is certainly the case for the SNL performance assessments, despite the fact that the PA models are somewhat simplified. McKay et al., (1979) and Iman and Conover (1982) developed a statistical sampling scheme for Monte Carlo simulations, called Latin Hypercube Sampling, that reduces the number of model runs but still achieves high precision in the estimate of the CCDF. The WIPP Performance Assessment Department is using this methodology.

The timing of an intrusive event has a large impact on the potential for radioactive material being released into the environment, and the importance of timing has a large impact on the computational resources of the WIPP Performance Assessment Department. The probability of a drilling event is estimated by the Poisson model (WIPP Performance Assessment Department, 1992, Volume 2). However, because of the computational demands of coupling random drilling with the parameter uncertainty discussed in the previous section, simplifying assumptions, in terms of fixed times for drilling at 1,000, 3,000, 5,000, 7,000, and 9,000 years, were made for the 1991 PA calculations. The 1992 calculations assumed drilling intrusions take place at 125, 175, 250, 1,000, 3,000, and 7,250 years.

The side benefit of a Monte Carlo uncertainty analysis is that it provides a set of input parameters and their associated performance measure values that allows further analyses, such as statistical sensitivity analyses (Helton et al., 1991) to determine which parameters are the most important in determining the value of the performance measure. Sensitivity analyses help focus scientific and site investigations by providing information that will ultimately be used for the performance assessments.

The primary focus of the SNL sensitivity and uncertainty analyses to date has been on the parameters within the models. However, this approach cannot adequately deal with uncertainties in the choice of the conceptual models of the physical processes that affect repository performance. The issues related to the choice of the constitutive relationships that are embodied in a performance assessment code are often more important in determining the adequacy of the performance assessment than the effects of parameter uncertainty. That information can be obtained by comparing results of the principal investigators' constitutive models with those of the performance assessment models. This is particularly important, since the performance assessment models tend to be chosen for computational efficiency for the Monte Carlo computing environment. More formal sensitivity studies that compare the results of the constitutive and performance assessment models will help to establish the appropriateness and adequacy of the PA models.

2.2.5 Probabilistic Approach and the CCDF

The probabilistic requirements of the §191.13 standard are partially met by the Monte Carlo uncertainty analysis methods described in the previous section; a CCDF can be computed easily from the results of a Monte Carlo analysis. The Monte Carlo methods work well when dealing with the parameter uncertainty within a specific scenario. However, the need to evaluate the results of multiple scenarios, such as disruptive events, and combine them into a single CCDF requires estimates of the probabilities of occurrence of the scenarios. **Figure 2-8** illustrates how the consequences (cS_i) of the individual scenarios S_i are combined into the overall CCDF using the weighting factors pS_i, which are the probability of occurrence of the scenarios.

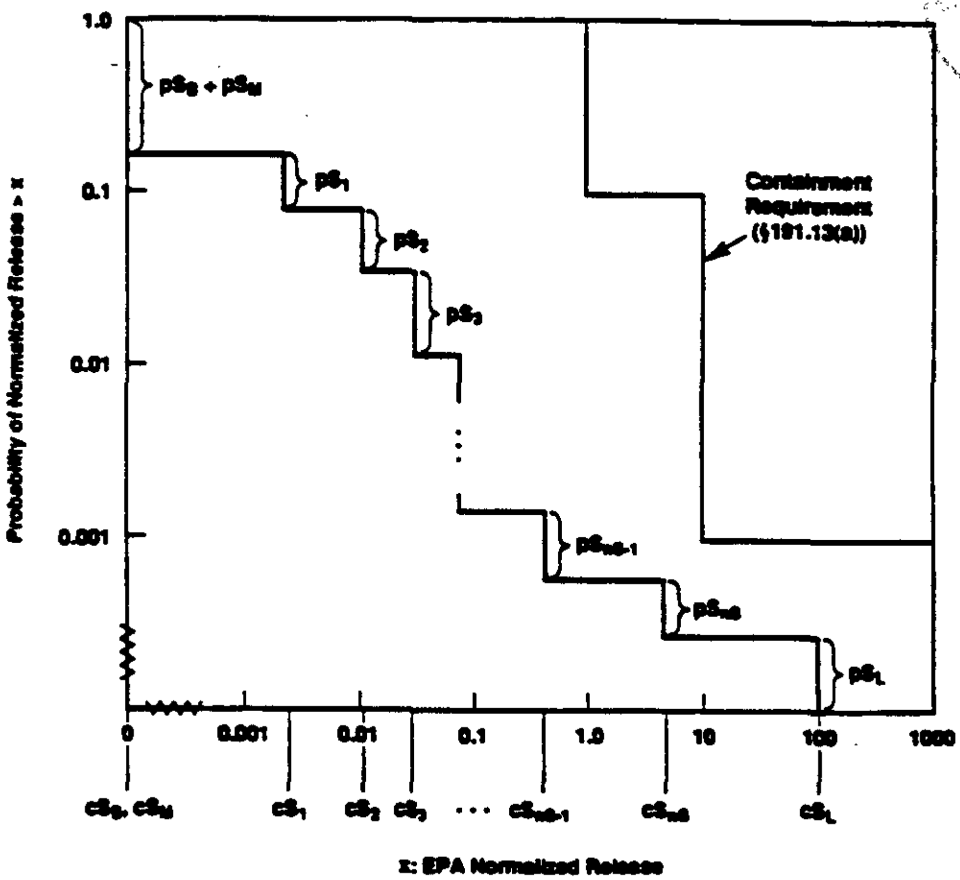


Figure 2-8. **Construction of a CCDF for Comparison with the EPA Release Limits. (Note that the location of cS_B at the lower left of the plot is correct for the WIPP–where no releases are predicted from the undisturbed base case–but is not a generic requirement for all sites.**

As discussed previously, Monte Carlo techniques are used to characterize the uncertainty in the results by repeatedly sampling the uncertain parameters. Such an analysis produces a family of CCDFs. The variability within the family of CCDFs obtained from the sampling can be represented by the mean, median, and 10% and 90% quantile CCDFs in **Figure 2-9**.

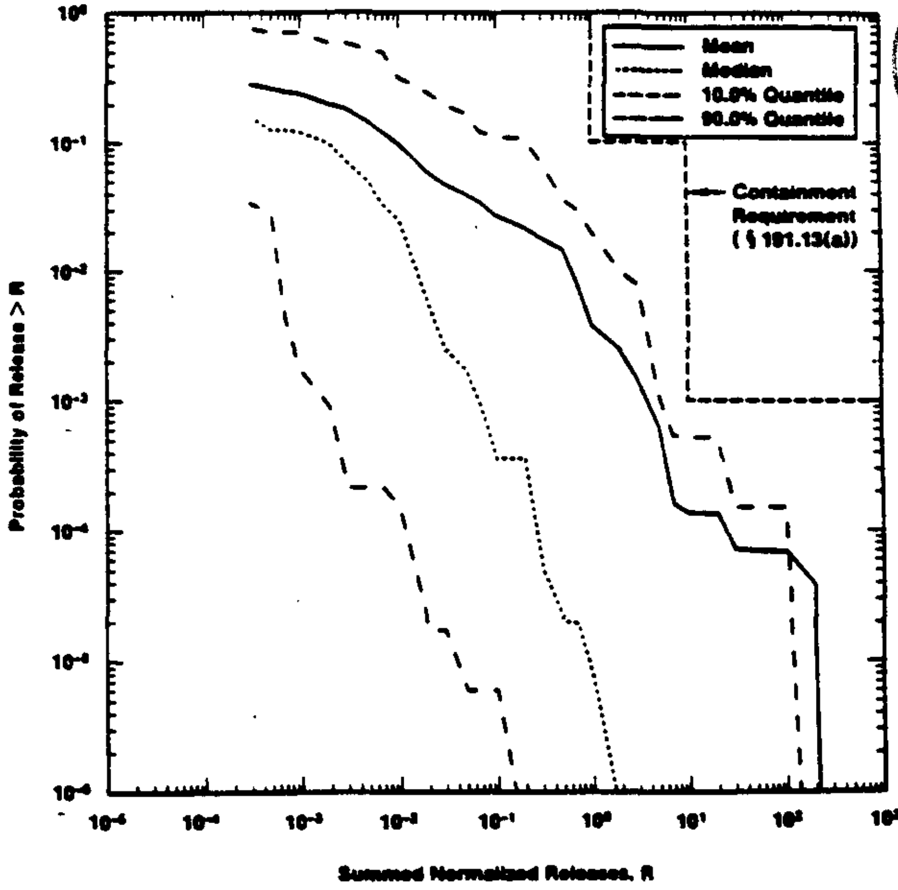


Figure 2-9. Example Summary Curves Derived from an Estimated Distribution of CCDFs. Curves were obtained by calculating the mean and indicated percentiles for each consequence value (PA, 1992, 2, Figure 3-3).

The SNL PA department (1992 PA, Volume 2) recognizes that the CCDFs cannot describe conceptual model uncertainty because, by their construction, they are conditional on the assumptions of the analysis. To evaluate conceptual model uncertainty, the complete Monte Carlo analysis is repeated for alternative conceptual models by changing only those portions of the analysis specific to the alternative models. The shift in the location of the CCDF relative to the others gives an indication of the uncertainty introduced by alternative conceptual models; it is also an indication of the sensitivity of the conceptual model itself in terms of affecting disposal system performance.

Although these conceptual model sensitivity and uncertainty analyses provide valuable information, they cannot address differences in the conceptual model that cannot be described by the existing PA models. These analyses may not necessarily adequately address the different conceptual models represented by the more detailed constitutive models of the principal investigators as discussed in the previous section.

2.3 40 CFR PART 268.6

The long-term performance requirements of 40 CFR 268.6 are not as detailed or prescriptive from a methodological standpoint as those of 40 CFR 191. The regulation requires demonstration "to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit . . . for as long as the wastes remain hazardous" (40 CFR 268.6(a), U.S. EPA, 1986).

The EPA's draft guidance manual for 40 CFR 268.6 describes general requirements for what must be addressed in a no-migration determination petition. Examples of the requirements are that the relevant physical processes must be addressed, some type of quantitative modeling is desirable, and formal quality assurance/quality control measures must be applied to the computer codes. Specific technical details are to be worked out in negotiations with the EPA.

2.4 WESTINGHOUSE APPROACH TO 40 CFR PART 268.6

The basis of the PART's review of the Westinghouse approach to compliance with 40 CFR Part 268.6 was a presentation by Westinghouse Waste Isolation Division staff and their contractors. To facilitate comparison of the SNL and WID approaches to performance assessment, the outline of the discussion follows the same format as used in Subsection 2.2.

In contrast to the SNL approach to PA modeling, which uses code for which published documentation is not publicly available, the WID PA approach uses numerical models that are relatively simple to use and preferably "off the shelf," so that they can be easily transferred to EPA for execution and evaluation.

2.4.1 General Description of Scenarios

The 40 CFR Part 268.6 regulations do not specifically require that human intrusion be addressed to demonstrate long-term performance. As implied by the presentation by WID and its contractor staff, the scenarios that are being addressed pertain to expected repository conditions and are based on the description of the model selection phase. It has been stated in the two No-Migration Determination Annual Reports (DOE/WIPP 91-059 and DOE/WIPP 92-057) and in the presentation that the WID PA conceptual model is consistent with the SNL PA conceptual model for 40 CFR Part 191 Subpart B. In fact, the results for PA that are reported in these two documents are those reported in the annual performance assessments for 40 CFR 191, although they are results for radionuclides, and 40 CFR 268.6 pertains to hazardous constituents.

2.4.2 Performance Measure

The performance measure is not defined specifically in the regulations as it is for the containment requirements in §191.13 and the individual and groundwater protection in §191.15, and §191.16, respectively. Under 40 CFR 268.6 there is only what might be construed as an overall system performance requirement — i.e., no migration beyond the disposal unit boundary for as long as the wastes remain hazardous (Subsection 1.3.1).

2.4.3 Modeling Approach

The WID modeling approach is divided into near- and far-field categories. The near-field model requires a site-specific description of the repository engineered barrier system in order to assess the ability of the system to prevent the transport of hazardous components (i.e., volatile organic compounds, non-volatile organics and heavy metals) in the waste to the unit boundary. The Design Analysis Model (DAM), which was used to analyze the options for waste treatment for the Engineered Alternatives Study (DOE/WIPP 91-007), is proposed for this analysis. The PA models used by SNL for comparison with 40 CFR 191 Subpart B requirements do not describe the performance of the engineered barrier of candidate room, panel and shaft seals.

The WID approach to PA accepts the physical processes that the SNL Performance Assessment Department has determined to be important for far-field performance. The WID model selection process focuses on deterministic models that are considered readily available. Using criteria that had to do with availability of documentation and published verification exercises, WID selected the TOUGH2 code. The desired capabilities for the WID far-field model are given in **Table 2-2**.

Table 2-2. Desired Capability for WID Far-Field Performance Assessment Modeling

Two-phase flow	Thermal effects
Multi-phase, multi-component transport	Transport processes
	Advection
Transient effects	Dispersion
High dimensionality	Diffusion
Material properties	Chemical interactions
Anisotropy	Sorption
Heterogeneity	Decay
	Dissolution/precipitation
	Ion Exchange
	Leaching

2.4.4 Sensitivity and Uncertainty Analyses

WID has chosen to utilize the same methodology for sensitivity and uncertainty analyses that are used by the Sandia Performance Assessment Department for 40 CFR Part 191 Subpart B. This includes a Monte Carlo approach to a deterministic model, using Latin Hypercube Sampling of the model input, and rank correlation techniques to induce known dependencies among the input variables. The current plans are to do uncertainty and sensitivity analyses separately for the DAM and TOUGH2 models. No analyses have been completed to date.

2.4.5 Probabilistic Approach and the CCDF

The language of 40 CFR Part 268.6 does not specify a probabilistic approach to demonstrating compliance. From a regulatory standpoint, it is not required in the performance assessment methodology to include the calculation of the CCDF driven by §191.13(a). Demonstrating compliance with a deterministic standard and addressing uncertainty by means of quantitative and qualitative analyses may be easier than using a probabilistic standard. From a methodological standpoint, estimating small exceedance probabilities, such as those used in the §191.13(a) standard, requires estimating the size of the tails of a CDF. Estimates of the tails are subject to more uncertainty than estimates of the mean or median of a CDF.

3.0 WIPP CONCEPTUAL MODELS AND IDENTIFICATION OF ISSUES

In the preceding section, the Sandia National Laboratory (SNL), Westinghouse, and PART approaches to performance assessment methodology were discussed. Constructing the total system PAs of the WIPP repository involves developing appropriate conceptual model(s) of the WIPP site and disposal system, both for now and for future time periods (10,000 years). This is extremely important to system PA and the planning of data acquisition as well as to laboratory and field scale experimental programs (as described in Subsection 3.1). Section 3 describes two types of conceptual models: Pre-WIPP Facility Conceptual Models and Post-Decommissioning Conceptual Models. The Pre-WIPP Conceptual Models are discussed in Subsection 3.2 in terms of the pathways that existed before construction of the WIPP facility from the proposed location of the waste panels to the compliance boundaries, and in terms of significant driving forces and processes that govern the movement of fluids or the transport of dissolved chemical species contained in these fluids. Subsection 3.3 addresses Post-Decommissioning Conceptual Models at an outline level, and describes the pathways, driving forces, and processes that could be expected to result through time from interactions between the components of the natural system, the waste, and any of the engineered emplacements or components of the disposal system.

3.1 BASIC WIPP DISPOSAL SYSTEM CONCEPTS AND HIGH LEVEL ISSUES

The basic WIPP disposal concept is rooted in the promising features of salt deposits identified by NAS in the early 1950s (see Subsection 2.2). The WIPP site is part of a vast Permian age salt deposit located in a relatively stable geological area with little earthquake activity (**Figures 3-1** and **3-2**). Waste emplaced in the mined rooms of the disposal panels (**Figure 3-3**) will eventually be encapsulated and become part of the stable rock of the Salado Formation, as a result of the natural "plastic-like" quality of salt that enables it to flow or creep under the effects of heat and stress found at the 655 m (2,150 ft) proposed repository depth. Isolation of the radioactive waste from the accessible environment and retention of the hazardous waste within the boundaries of the disposal unit for the required regulatory periods is expected because of the waste encapsulation, the virtually impervious nature of the undisturbed Salado Formation salt deposits at repository depths (permeabilities near 10^{-22} m^2), and the absence of flowing groundwaters within the formation for the transport of any leached wastes. The various issues that must be addressed are a result of trying to provide a credible basis for the different assumptions in this basic design concept; (e.g., could gas generation prevent encapsulation and sealing of the wastes in the rooms and seals? or are there natural processes such as dissolution or breccia pipes that could breach the Salado?). The great difficulties are mainly associated with the various uncertainties that arise because of the long time frames for which repository performance must be demonstrated.

3.1.1 High Level Regulatory Related Issues

The highest level regulatory issue is related to the differences in approach between the regulations applicable to the hazardous wastes and the regulations applicable to the radioactive wastes as summarized below.

- Disposal of radioactive wastes under 40 CFR 191, recognizing the uncertainties in predicting behavior over the long time periods that radioactive wastes remain hazardous, is based on the concept of a waste isolation system within a 5 km (3 mi) controlled zone (**Figure 3-4**). This

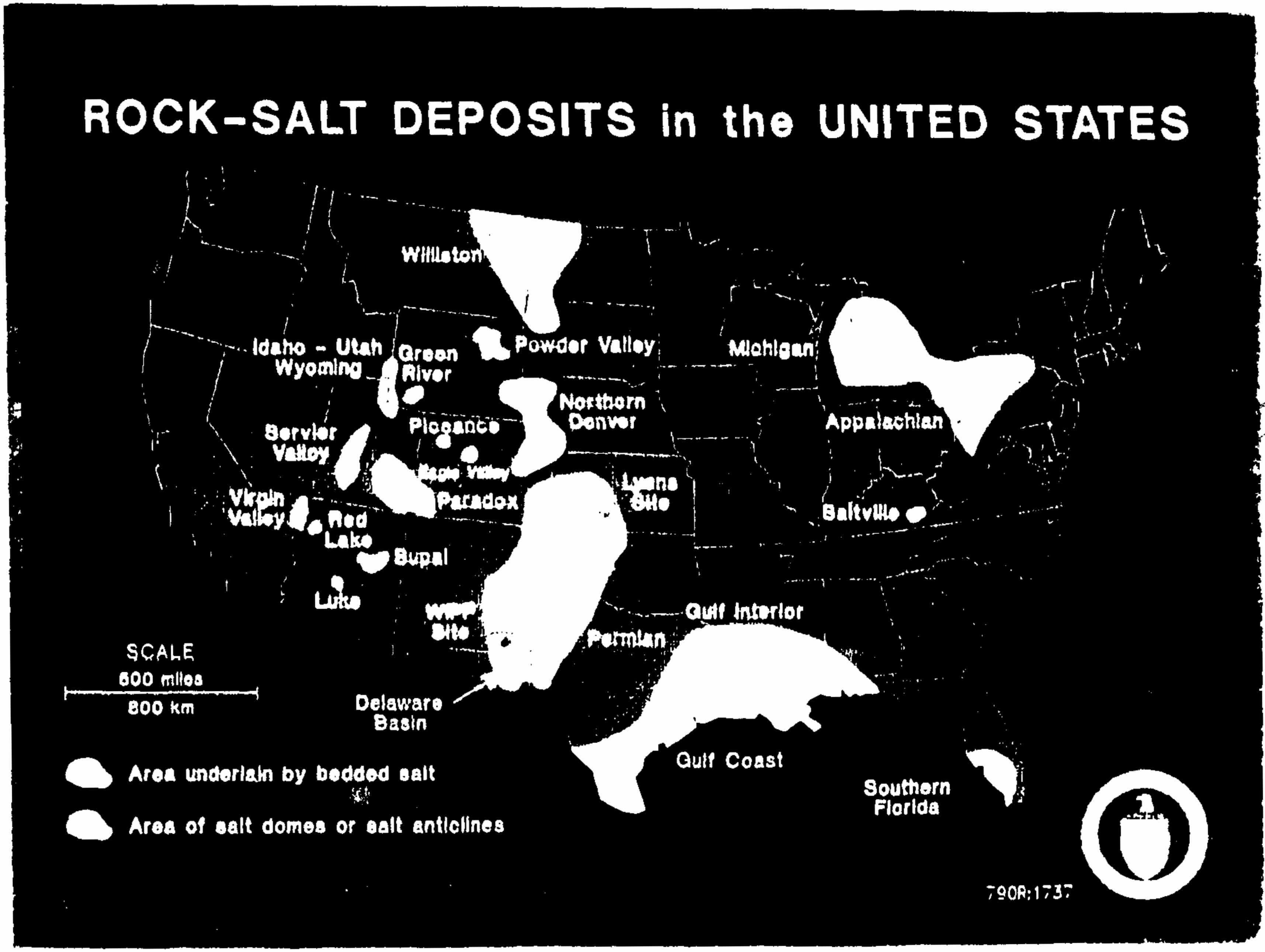


Figure 3-1. Location of Various Rock-Salt Deposits in the United States.

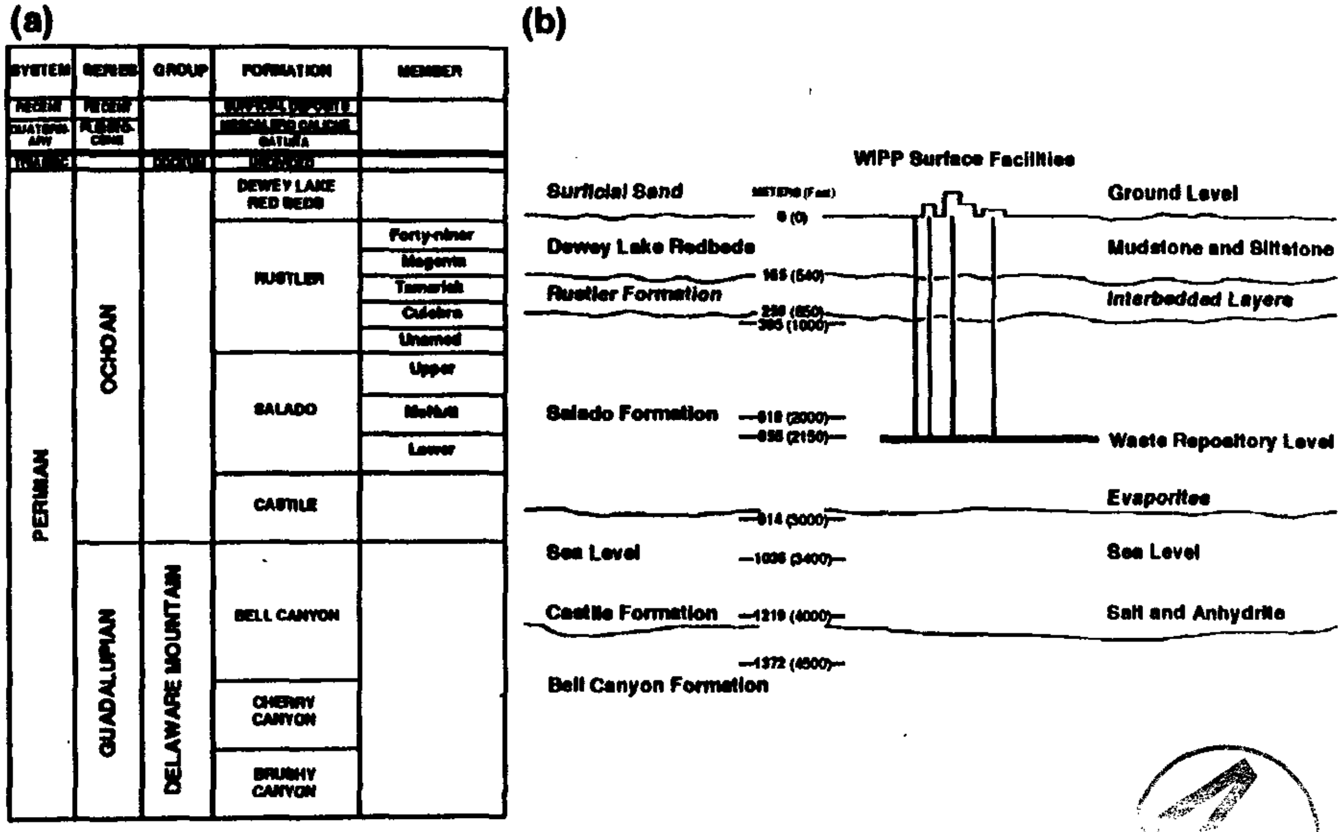
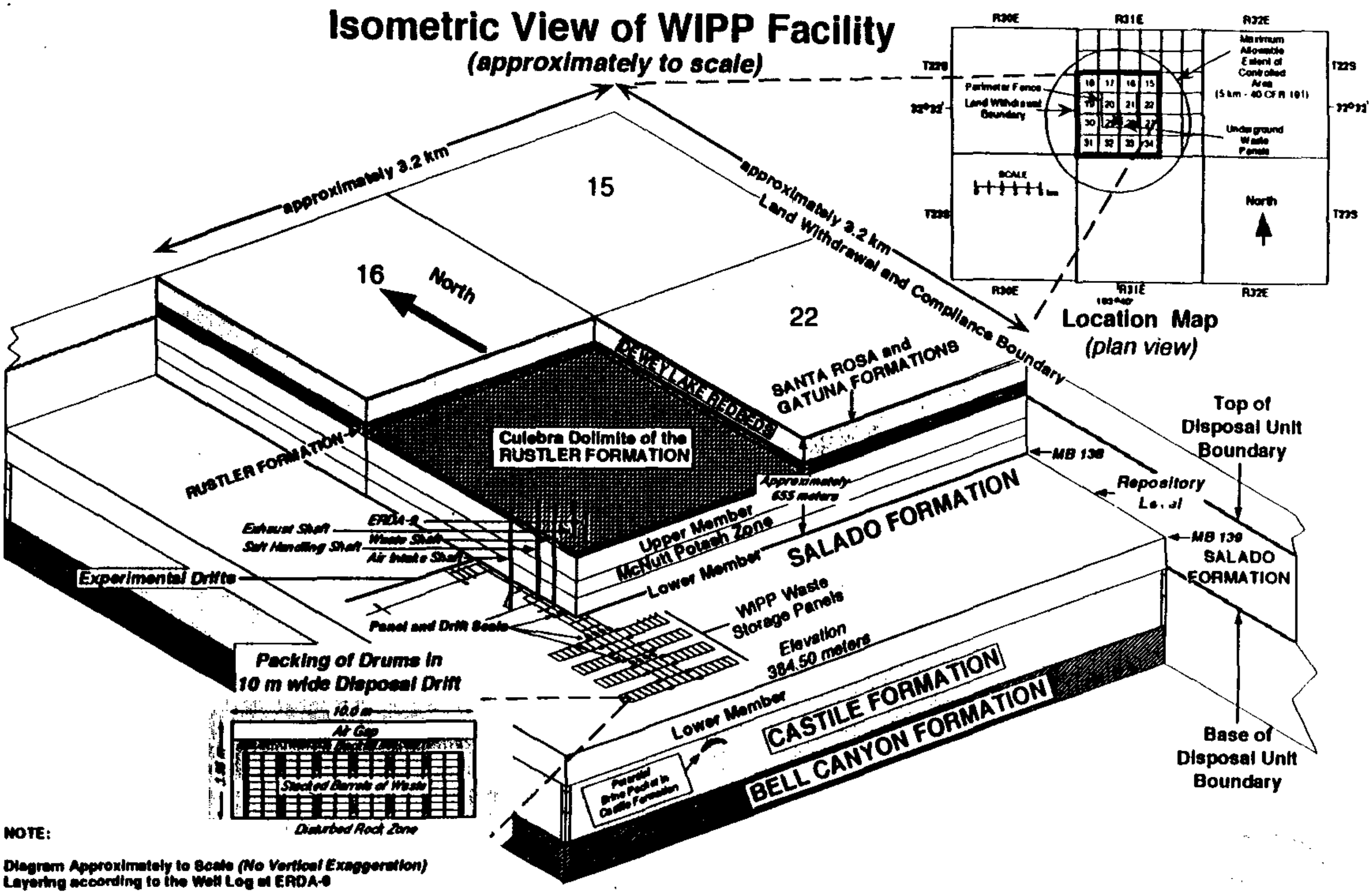


Figure 3-2. (a) WIPP-Area Stratigraphic Column and (b) the Geologic Profile at WIPP Illustrating the Location of the WIPP Underground Workings in the Profile.



NOTE:

Diagram Approximately to Scale *(No Vertical Exaggeration)*
Layering according to the Well Log at ERDA-9

Expanded Three-Dimensional Cutaway View of the WIPP SITE (approximately to scale
WIPP Underground. Access Shafts, Location of
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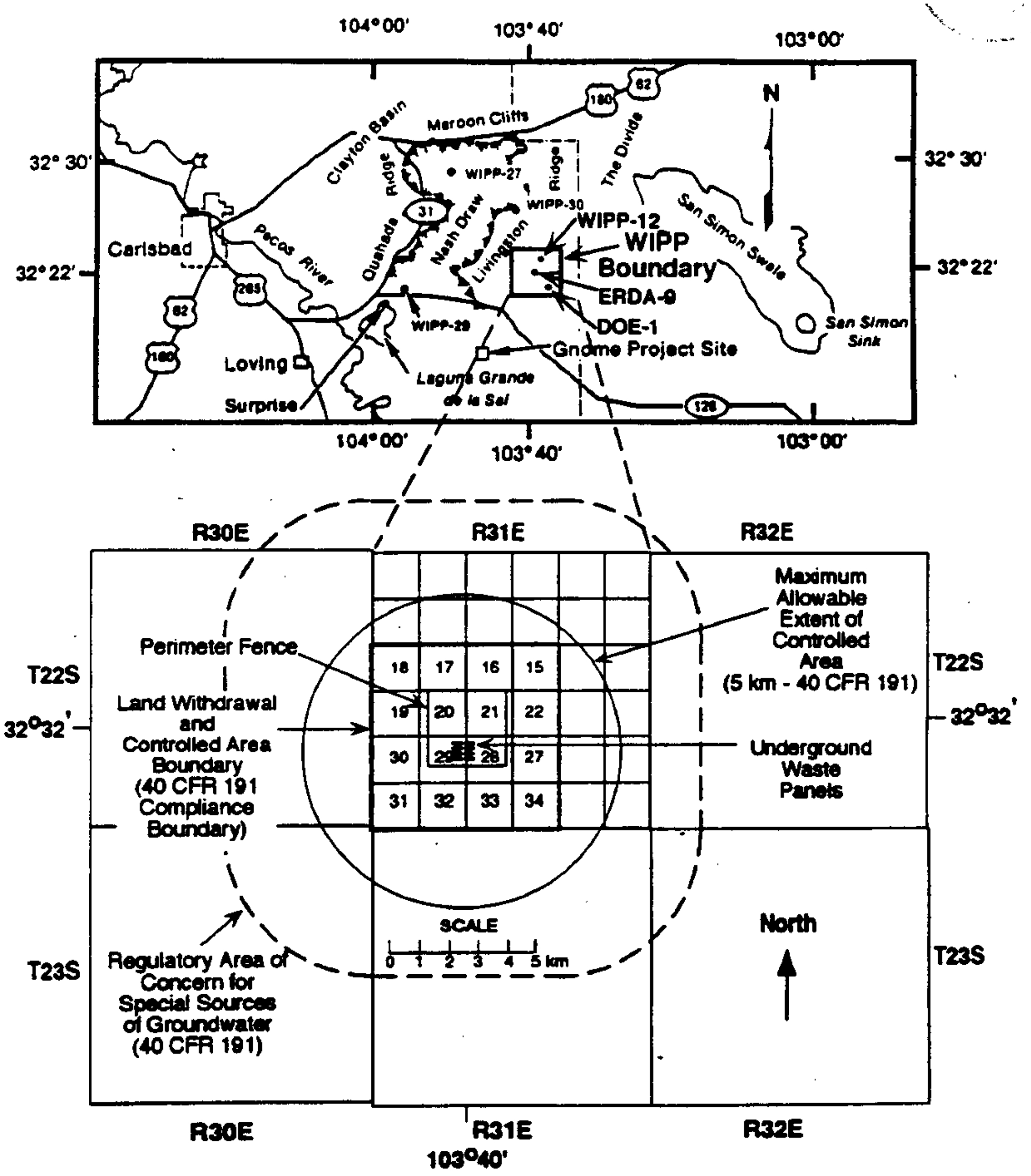


Figure 3-4. **Plan View Location Map Showing the Perimeter Fence, Land Withdrawal Boundary, Maximum Allowable Extent of the Controlled Area, and Compliance Boundary (coincident with the land withdrawal boundary) for the WIPP Site Relative to the WIPP Underground Workings.**

zone defines the boundary of the isolation system, which consists of multiple natural and engineered barriers (including the waste itself) to control, minimize, or eliminate waste release and account for these uncertainties through the redundancy of multiple independent barriers (Subsections 1.3.2 and 1.3.3).

- Disposal of hazardous wastes under 40 CFR 268 requires having detailed knowledge of the waste form so that appropriate treatment can be prescribed for assurance of disposal safety (Subsection 1.3.2). Co-disposal of untreated hazardous wastes that are radioactive or contaminated with radioactivity, as proposed by the DOE, is through the exemption provision (40 CFR 268.6) that requires a demonstration of no migration beyond the disposal unit or injection zone (Subsection 1.3.2).

Some of the difficulties created by these differences have already been resolved, but others remain.

For 40 CFR 191, the disposal system design must be shown to meet three numerical requirements: isolation, individual protection, and groundwater protection. The repository design is also constrained through the assurance requirement to use multiple natural and engineered barriers (which can include the waste itself) within a controlled volume excluded from the accessible environment, to incorporate recoverability, to provide for monitoring, to use active and passive institutional controls, and to evaluate adverse factors related to site selection.

Under 40 CFR 268, any design requirements are actually for the waste form itself, which must meet very specific treatment requirements based on careful characterization of the waste. There is also no specified concept of a disposal system with design requirements and constraints embodied in 40 CFR 268 as there is in 40 CFR 191. DOE expects to petition for an exemption to allow the land disposal of untreated, prohibited, hazardous wastes through preparation of a demonstration of no migration, as provided for under 40 CFR 268.6. Under 40 CFR 268.6, there is only what might be construed as an overall system performance requirement - i.e., no migration beyond the disposal unit boundary for as long as the wastes remain hazardous (Subsection 2.3.2). Issues have been raised regarding what is meant by the following phrases from 40 CFR 268.6 with respect to the WIPP. These have been resolved as follows.

- *"No-migration."* Resolution - above health-based limits (55 FR 220, pg. 47704). The issue is whether the possible movement of even one molecule outside the disposal unit boundary, or the taking of one reading above a detection limit, constitutes a violation of no-migration. The resolution of the issue is to adopt a position that no-migration requires that the measured or predicted concentration at or beyond the disposal unit boundary be below health-based concentration limits.
- "*Disposal unit boundary.*" Resolution - top and bottom of the Salado Formation and laterally where the vertical extension of the land withdrawal boundary intersects with the Salado Formation (Figure 2.11, 55 FR 220 pg. 47704).
- "*As long as the waste remains hazardous.*" Resolution - 10,000 years "No migration variances to the hazardous waste land disposal prohibitions: A Guidance Manual for Petitioners." draft July 1992, U.S. EPA, Office of Solid Waste, Washington, D.C.

A potential issue that arises related to "no migration," now being defined as dependent on health-based release limits, is that the treatment and/or removal of hazardous wastes from any part of the proposed waste streams could reduce the quantity of hazardous waste potentially available for release, and thus reduce migration.

3.1.2 WIPP Design Objectives/Constraints

The two disposal system concepts of 40 CFR 191 and 40 CFR 268, with their different design objectives/constraints, can be viewed as a single waste disposal system concept, in which the disposal system, the basic design requirements, and constraints for the full disposal system are as defined for 40 CFR 191. However, the requirements of 40 CFR 268.6 impose an additional performance objective for *the disposal unit component of the 40 CFR 191 disposal system (i.e., for the Salado Formation and all* components of the disposal system within it). This additional requirement is that there be no migration of hazardous wastes above health-based limits beyond the disposal unit boundary (Figure 3-3) for the next 10,000 years.

3.1.3 WIPP Compliance and Other Boundaries

The regulations define the maximum extent limits for a controlled area (Subsections 2.3.1.4 and Figure 3-4) that can be identified by passive institutional controls in order to define the lateral limits of the controlled volume of the subsurface that is excluded from the accessible environment. This boundary between the controlled zone of the subsurface (i.e. the geologic disposal system) and the accessible environment forms the compliance boundary. The LWA established the subsurface below the 4-mile-by-4 mile land withdrawal boundary (i.e., subsurface below Sections 16-22 and Sections 27-34 R31E, T22S) as the controlled volume whose outer boundary forms the compliance boundary for 40 CFR 191, as discussed in Subsection 1.3.3. The dashed line around the land withdrawal boundary in Figure 3-4 illustrates the regulatory area of concern for special sources of groundwater.

3.2 CONCEPTUAL MODEL, THE ASSUMPTIONS AND ISSUES

The information discussed in this subsection is needed to develop the various issues that the PART review team has identified and considered in evaluating the adequacy of WIPP PA, measurement, and experimental activities, as well as the decision making process that relates to these activities.

Constructing the total system PAs of the WIPP repository involves developing appropriate conceptual model(s) of the WIPP site and disposal system (Subsection 3.2.2) both for now and for future time periods (at least 10, 000 years). The conceptual model(s) must describe

- the current state of the WIPP site;
- the various projected likely, as well as unlikely, future states of the WIPP site and disposal system components, so that estimates of the disposal system performance (i.e., projected release and movement of both hazardous and radioactive waste beyond 40 CFR 191 compliance and 40 CFR 268 disposal unit boundaries) can be made for various plausible future scenarios or states that could result from the disposal system emplacement as a result of interactions between the wastes and other components of the disposal system;
- plausible and likely natural processes and events; and
- human intrusion events of severity no greater than mandated by the regulations (Subsections 2.3 and 3.1).

Conceptual modeling is extremely important to system PA and the planning of data acquisition, as well as to laboratory and field scale experimental programs. The need for subjective judgments in the development of conceptual models arises as a result of the uncertainty associated with geologic systems. due to their complexity and variability, and the limited number of observations in both space and time. Plausible alternative conceptual models, based on available information and understanding and of appropriate complexity to address the objectives of the effort, must be established. Only then can appropriate system response and parameter measurements be identified, with the correct spatial and temporal frequencies to reveal the true nature of the system being observed.

A conceptual model, no matter how technically complex, will always be a simplified picture of the real system. Current understanding, data-gathering capabilities, and computer technology simply do not allow a geologic disposal system to be described in every detail. Conceptual model development, therefore, involves forming a sufficiently representative simplified picture of those aspects of the system which are important in demonstrating compliance (Subsection 3.1). Development of plausible conceptual models requires identification of (1) the relevant and interacting processes that control the important attributes of disposal system behavior; (2) appropriate ways to parameterize the system, and (3) the appropriate way to extrapolate knowledge of these processes, measurements, and observation into the spatial and sometimes temporal distributions of parameters and response that are required to model the current and future likely states of the system. Various technical issues considered and addressed, the decisions, the supporting reasoning, and the parameters and observations used to form this sufficiently representative simplified picture (i.e., the conceptual model) must be clearly identified and documented (Subsection 3.1.2). Technical issues are simply questions about what constitutes the best way to describe the system to be modeled in terms of relevant pathways, processes, parameterization, and numerical models. The issues stem from limitations in current physical and chemical understanding, data gathering capabilities, and computer modeling capabilities. In many cases, these technical issues cannot be absolutely resolved.

3.2.1 High Level Description of the WIPP Disposal System Conceptual Models

This subsection contains a high level discussion limited to identifying the major issues and assumptions that must be resolved and justified to provide the required support for the various conceptual models that form the basis of both the mathematical and the numerical models used for compliance analyses (Subsection 3.1). Clear identification and documentation of these important conceptual model issues and assumptions and the way they were resolved and justified (including the laboratory and field measurements and other experimental evidence, expert panel findings, or numerical studies) are key to attaining a reasonable expectation (or degree of certainty) with regard to the results from these compliance models (substeps 2.1.3, 2.1.4, 2.2.5.1 and 2.2.5.3 of Subsection 1.4.3.1).

Compliance analysis models, for the various compliance time frames of interest (Subsections 1.3.1 and 1.3.3), must be able to predict short- and long-term behavior as a result of the changing states of the various components of the WIPP disposal system (e.g., the rooms, drifts, various panel, shaft, and drift seals discussed in Subsection 3.2.2), as well as the integrated behavior of the overall WIPP disposal system in response to both natural processes and events and human intrusion events of limited severity, as specified in the regulations (Subsections 3.1, 1.3.2, and 1.3.3). Expressing this in terms of Kaplan and Garrick's (1981) risk triplet, which is the basis of the WIPP PA methodology and which is discussed in the 1992 WIPP PA (SAND92-0700/1), these compliance models must predict, "the consequences of these things (scenarios) happening" as a result of "What can happen? (scenarios)," and these various possible consequences can be weighted by "how likely are things to happen? (probabilities of scenarios)."

While, as discussed by Guzowski (SAND89-7149, 1990), the term "scenario" is not defined and does not appear in the actual regulations (and only once in Appendix B of 40 CFR 191), scenarios are commonly taken to be those combinations of continuous processes (e.g., long-term slowly acting agents such as dissolutioning and climate change) and events (e.g., short time frame changes such as emplacement of the WIPP repository, human intrusion through exploratory drilling, or faulting in response to an earthquake) that result in a significant change in the state of the disposal system or its components. Therefore, the consideration of the following kinds of changes in important conceptual model factors is required:

- emergence of new or previously ignorable pathways or interconnections of previously isolated components, or cessation of existing pathways or interconnections;
- emergence of new or previously ignorable driving forces, significant changes in their values, or their cessation;
- emergence of new or previously ignorable mechanisms, or their cessation;
- significant changes in parameter values, the applicable parameters, and/or the spatial and/or temporal scales of the parameters;
- changes to other important conceptual model factors.

As a result, conceptual modeling cannot be carried out in isolation from the scenario analysis (which identifies these states and their likelihood) and vice versa. This is because the conceptual models must reflect these various scenarios (i.e., system states) and the scenario analysis must reflect any subsequent change in system state that might result from the long-term effects of the pathways, processes, and interactions identified through the conceptual modeling (e.g., development of a new pathway related to dissolutioning, fracturing due to gas pressure build-up).

In some sense, the separate steps of scenario analysis and conceptual modeling are more related to a limitation in current system modeling capability. Most of the component models used in the disposal system model assume fixed states for fixed spatial and time scales and for a fixed set of processes. Therefore, they cannot easily deal with temporal changes in model geometry, model scale, parameters, model processes considered, and other factors required for stochastically modeling the likely pathways through future disposal system state space as a result of the associated uncertainties in disposal system characterization and understanding. To overcome these difficulties, there is a need to identify these likely discrete disposal system state sequences, so that time can be divided into the appropriate periods and the appropriate fixed state models can be selected, interconnected and applied to determine consequence. To develop the overall disposal system conceptual and PA model, as well as the various disposal system component conceptual and PA models, approaches (SAND92-0700/2, 1992; SAND91-0893/1, 1991; SAND89-7149, 1990; and Cranwell et al., SAND80-1429, 1990) are required for selecting and screening these sequences of future disposal system states and for determining the probability of occurrence of each sequence. During the PART discussions with EEG, an issue arose regarding scenarios which really applies to many aspects of the PA process. Are the scenario selection and the scenario implementation processes ever revisited? Of concern to the EEG group was the implementation of the cuttings scenario.

Perhaps a formal documented method for dealing with issue identification and resolution would provide the means to deal with these types of concerns.

3.2.2 Components of the WIPP Disposal System

The WIPP disposal system is composed of both natural and engineered components.

1) The natural barriers within the compliance boundary (or non-accessible environment, as described in Subsection 2.1.3.3) include the following primary and secondary natural barriers.
    a) The Salado Formation forms the primary natural barrier. It consists of that portion of the Salado Formation within the limits of the land withdrawal boundary (Figure 2.13). This primary barrier is also classified as the disposal unit under 40 CFR 268.6.
    b) The geological formations above the Salado Formation and below the land surface within the limits of the land withdrawal boundary (i.e., Rustler, Dewey Lake Redbeds, and others shown in Figure 3-2) form one group of secondary natural barriers, should pathways and the necessary driving forces develop that connect the waste storage panels in the Salado to these units and the accessible environment beyond the compliance boundary.
    c) The various geological formations below the Salado Formation within the limits of the land withdrawal boundary (i.e., Castile, Bell Canyon, Cherry Canyon, and others as shown in Figure 3-2) form an additional group of secondary natural barriers between the waste storage panels in the Salado and the accessible environment beyond the compliance boundary, should pathways and the necessary driving forces develop.
2) The current reference design for the repository and the various engineered components was developed by Bechtel in 1986 (SAND92-0700-3). The attributes of this reference design and the associated engineered barriers are described below.
    a) The waste itself (Figures 1-2 and 1-3) and the waste containers can be considered engineered components if their properties are such that non-negligible credit can be taken for their ability to control, minimize, or eliminate release of hazardous or radioactive components that they contain.
    b) The ten equivalent waste storage panels of the reference repository design, shown in plan view in Figure 3-5, provide for the disposal of the projected 6.2 million cubic feet of TRU waste (97% CH-TRU, 3% RH-TRU) (Subsection 1.2.1). Waste is to be stacked in drums (three high) or standard waste boxes (SWBs) (Figure 3-5) in the 10.0-m-wide-by-3.96-m-high (33-ft-wide-by-13-ft-high) waste disposal rooms, as illustrated in the blowup of Figure 3-3 and then each of the rooms and drifts are to be backfilled with tamped salt (60% theoretical density), leaving a 0.71 m (2.3 ft) air gap. The design capacity of each waste room is 6,804 drums or their equivalent in SWBs. It should be noted, however, that there is some uncertainty regarding the actual capacity, since final plans for the stacking of SWBs are uncertain (SAND92-0700-3).
    c) The 847 horizontal RH canister holes in each waste panel are to be 4.6 m (15 ft) deep and emplaced 2.4 m (8 ft) apart along the walls of the disposal rooms of the disposal panels, as illustrated in the blowup portion of Figure 3-5. This provides storage for the other 3% of the waste that is expected to be of higher activity and classified as RH-TRU waste (Subsection 1.2.1). It should be noted that there is some uncertainty regarding the actual capacity provided by the current design, since the proposed spacing provides for only 6000 m^3 of RH-TRU waste per panel, while intended reference design capacity is 7,080 m^3 (SAND92-0700-3).

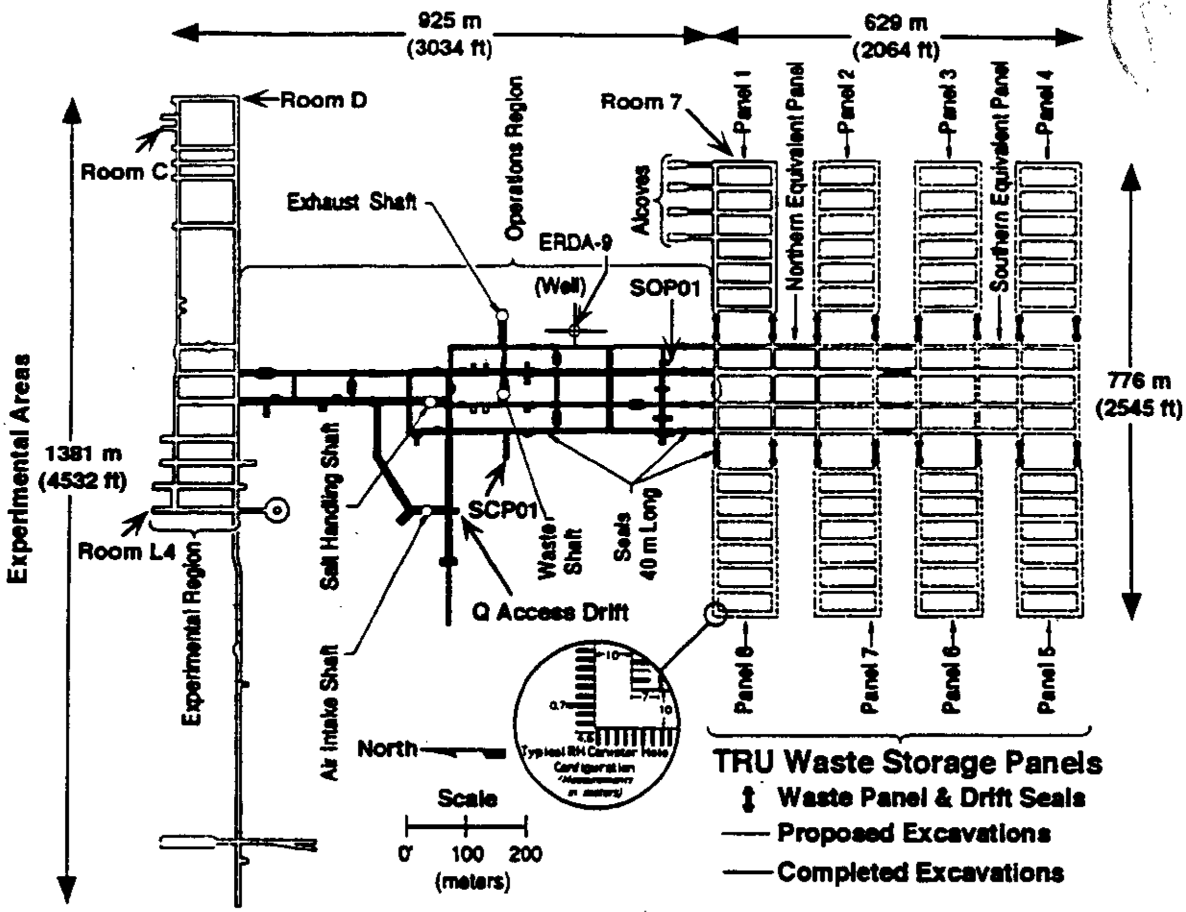


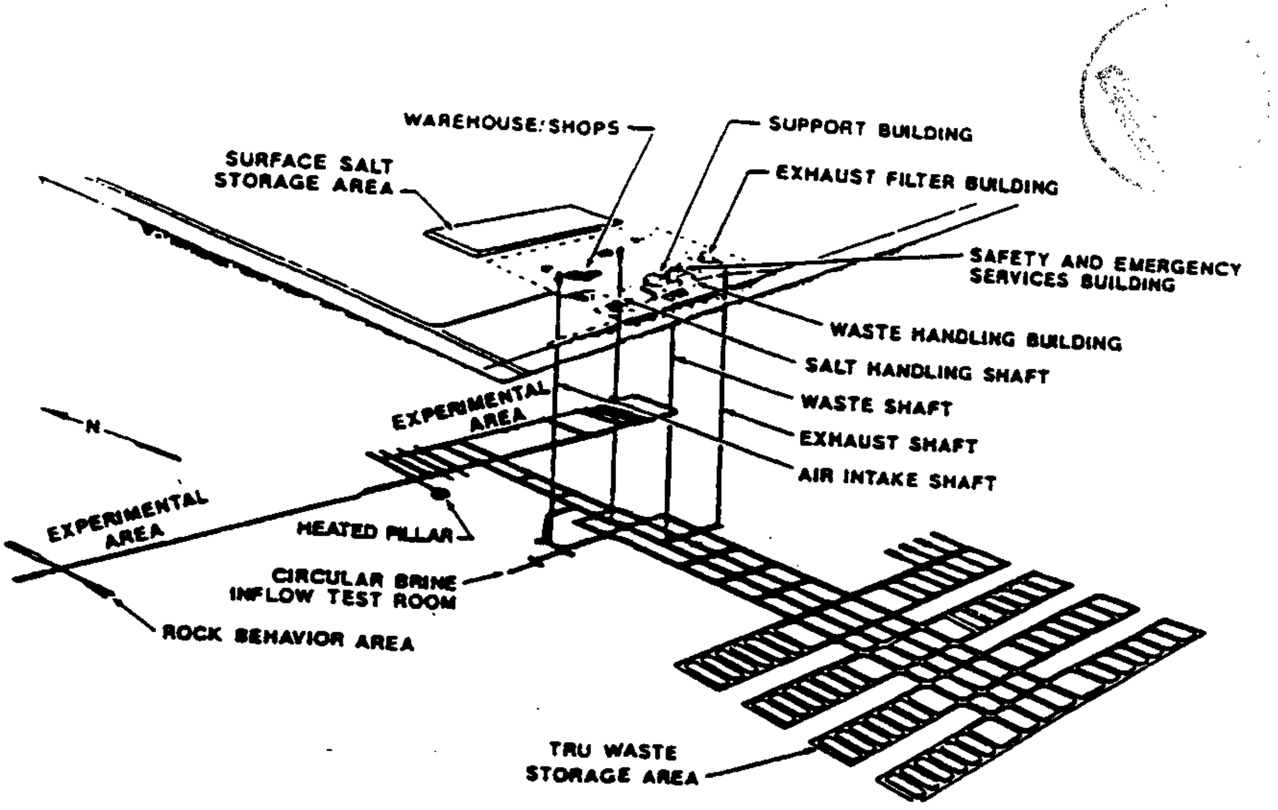
Figure 3-5. Plan View of WIPP Completed and Proposed Excavations.

d) The disposal system design also provides for the drifts of the operations area, the experimental area, and the test alcoves of the disposal area (Figure 3-5). The drifts of these areas will be sealed off from the disposal area and backfilled with crushed tamped salt during the disposal phase.

e) Access to and operation of the experimental region and the disposal system are provided for by the system of four access shafts (Figure 3-6 and 3-3).

f) The reference design sealing strategy for the Salado Formation (SAND92-700/3) makes the following assumptions.

- All openings in the waste storage area will be backfilled with tamped crushed salt (to at least 60% Salado halite density) that is presumed to reconsolidate eventually to nearly pre-emplacement density (95%) and permeabilities, as a result of creep closure of the openings;



Figures 3-6. **Isometric View of the WIPP Surface and Underground Footprint Looking to the Northeast. (Solid lines represent actual underground openings and hollow lines represent proposed waste panels.)**

- Redundant, accelerated (i.e., within approximately 100 years after installation), high quality sealing is to be provided for by fitting the specific portions of the access shafts and the waste disposal and operational area drifts indicated in Figure 3-5 and Figure 3-7 with combinations of short- and long-term engineered seal components (Figure 3-7). The short-term components of the engineered seals, typically concrete and clays specifically developed for WIPP, are expected to provide initial sealing until the long-term components, typically preconsolidated salts emplaced at 80% of the Salado halite density (e.g., in a manner similar to the experimental seal shown in Figure 3-8) become fully functional. Sealing of the four access shafts/penetrations of the Salado Formation is to be with a combination of lower shaft concrete plugs and preconsolidated crushed salt, as illustrated in Figure 3-7. The waste panel seals and the operational drift area seals are to be constructed as shown schematically in Figure 3-7 and located as illustrated in Figures 3-5 and 3-3.

g) The reference design sealing strategy for the water bearing units above the Salado Formation penetrated by the four access shafts (Figure 3-3) makes use of multi-component plugs constructed and located as illustrated in Figure 3-7 (SAND92-700/3).

The discussion of conceptual models that follows is divided into two parts: (1) Pre-WIPP Facility Conceptual Models; and (2) Post-Decommissioning Conceptual Models.

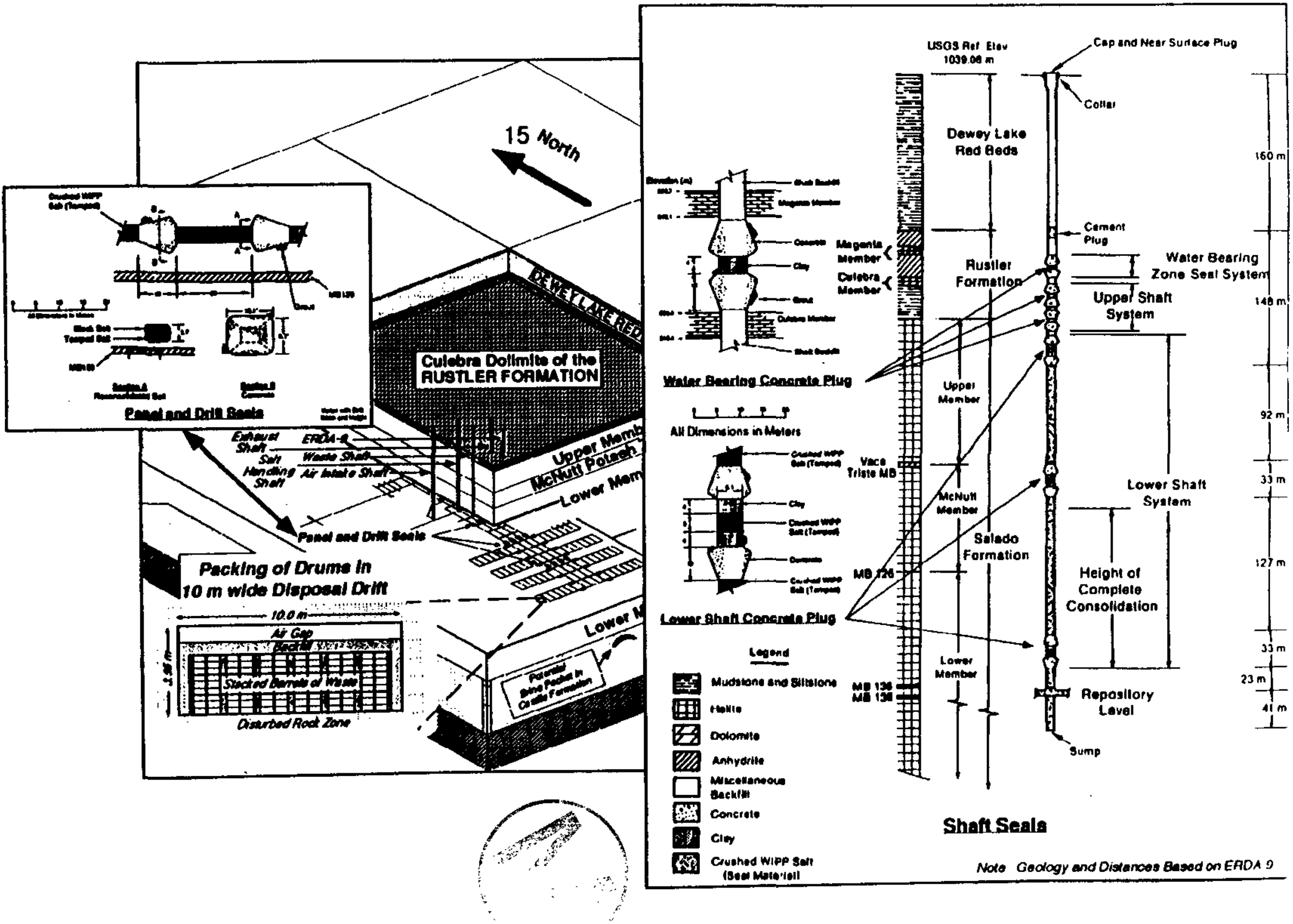


Figure 3-7. Reference Design Diagrams for Drift and Panel Seals, Typical Backfilled Access Shaft, Water Bearing Concrete Plugs, and Lower Shaft Concrete Plugs (after SAND91-0893/3, Nowak et al. 1990).

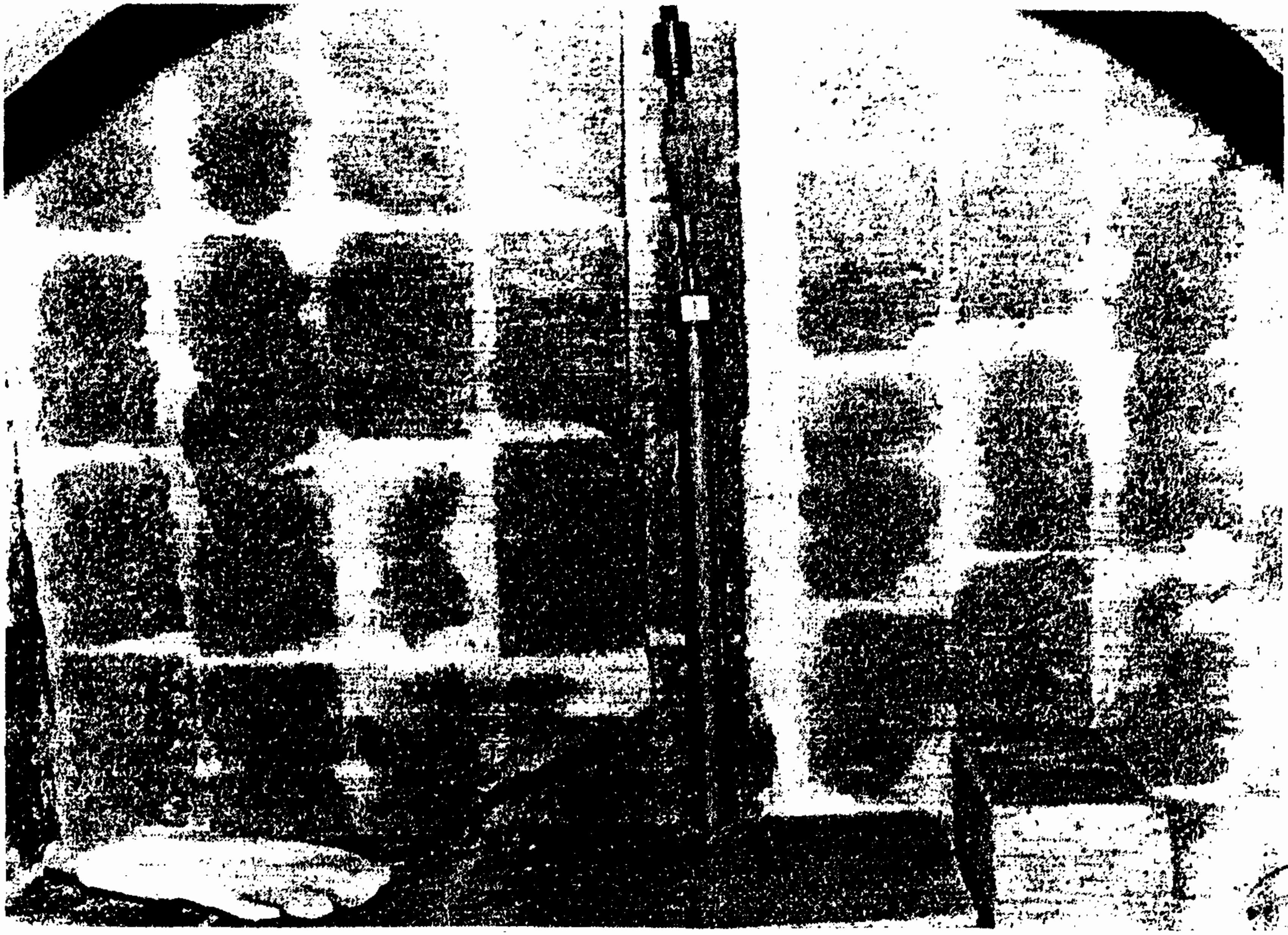


Figure 3-8. Example of Reconsolidated Salt Blocks Used to Seal a Horizontal Chamber at WIPP as Part of a Small-Scale Seal Performance Test in Room M (SAND87-2382, 1988).

3.2.2.1 Pre-WIPP Facility Conceptual Model

The pathways that existed before construction of the WIPP facility from the proposed location of the waste panels to the compliance boundaries (Subsection 3.1.3 and Figure 3-3), as well as the significant driving forces and processes that govern the movement of fluids or the transport of dissolved chemicals species contained in these fluids, are discussed in this subsection. All effects of the waste and its emplacement in the repository are ignored.

Connective disruptions, such as might be caused by human intrusion into the waste disposal area of the Salado by exploratory drilling, have the potential for interconnecting the waste disposal area to the significant water bearing formations above (the Rustler) and below (the Bell Canyon) the Salado Formation, and thus providing a transport path from the disposal rooms of the waste disposal area (Figure 3-3) to the accessible environment compliance boundary (40 CFR 191) illustrated in Figure 3-3 by three possible routes. These include transport through the Rustler, the Salado, and the Bell Canyon. The Castile Formation is not considered for transport since it is neither transmissive nor rechargeable, and it contains only isolated brine pockets. It is important to model the pre-WIPP undisturbed state, since this provides a way to demonstrate understanding of the geohydrologic system and setting, and it may provide the only chance to compare model results with data on such a large spatial scale and within such a long time frame. Discussions with SNL Department 6119 indicated that the PIs are currently undertaking this kind of regional modeling effort. The results from these initial efforts appear to be providing a better understanding of the temporal relationships between the five transmissive units of the Rustler (**Figure 3-9**) and their sources of and responses to recharge changes resulting from climate variations, as well as the potential for inter-communication between these units.

The Salado Formation (the most important natural barrier of the WIPP disposal system) is part of a thick (up to 4,000 m (13,000 ft)) sequence of marine sediments deposited in a structural depression known as the Delaware Basin that formed approximately 300 to 245 million years ago during the Late Pennsylvanian and Permian periods (SAND92-0700/2, 1992), and the WIPP site is located close to the northern boundary of the basin (**Figure 3-10**). A Guadalupian reef complex, consisting of the Capitan Limestone and equivalent carbonate units, forms the basin margins (Figure 3-10) and deep water shale, sandstones, and limestone of the Guadalupian Delaware Mountain Group (Figure 3-2), deposited during the initial period of rapid basin subsidence, form the basin floor for the Ochoan Series of evaporitic rocks (i.e., Dewey Lake, Rustler, Salado and Castile Formations) that eventually filled the basin during Permian time. In response to waning subsidence in the Late Permian time, the thick halite of the Salado extended across this Guadalupian reef complex, as illustrated in **Figure 3-11** (Mercer, 1983; SAND92.0700/2, 1992)

The Bell Canyon Formation, which is the uppermost member of this Guadalupian Delaware Mountain Group, is the first transmissive and rechargeable water bearing unit (total dissolved solids of 180,000 to 270,000 mg/l) below the Salado. Its upper units contain the most porous sandstones of the entire Delaware Mountain Group and are targets for hydrocarbon exploration (Mercer, 1983; SAND92-0700/2, 1992). The structure contours for the Lamar Shale, (the uppermost member of the Bell Canyon Formation {**Figure 3-12**}), illustrate the gentle dip to the east (approximately 1 degree) common to all the Permian units in the basin (Mercer, 1983). **Figure 3-13** shows the interpreted potentiometric surface for the upper part of the Bell Canyon. Mercer (1983) concludes that regional flow begins with waters entering in the Delaware and Guadalupe Mountains to the west and then, restricted by intervening siltstones,

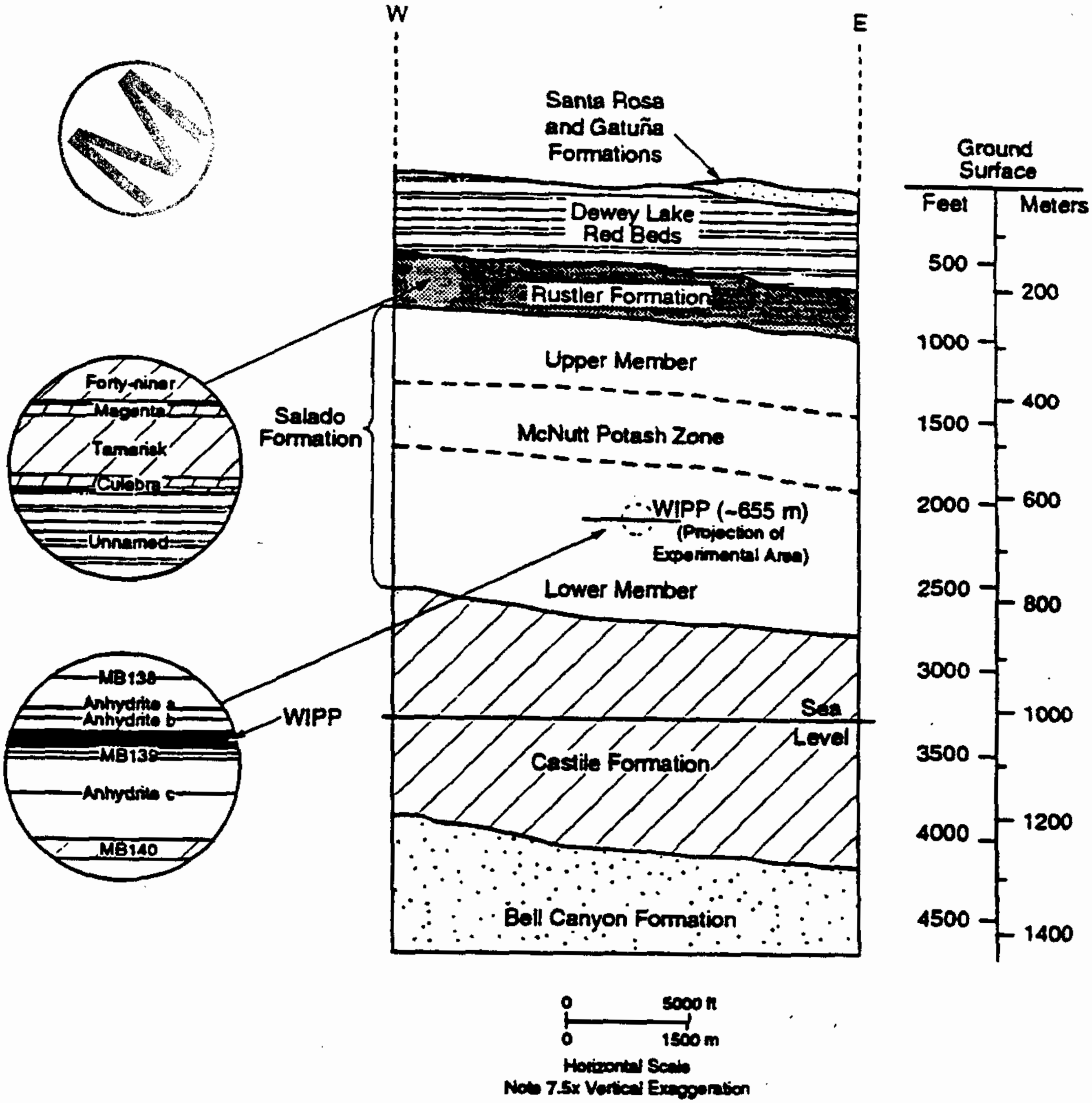


Figure 3-9. Generalized WIPP Stratigraphy Across the Land Withdrawal Area (after DOE/WIPP 89-011, 1993).

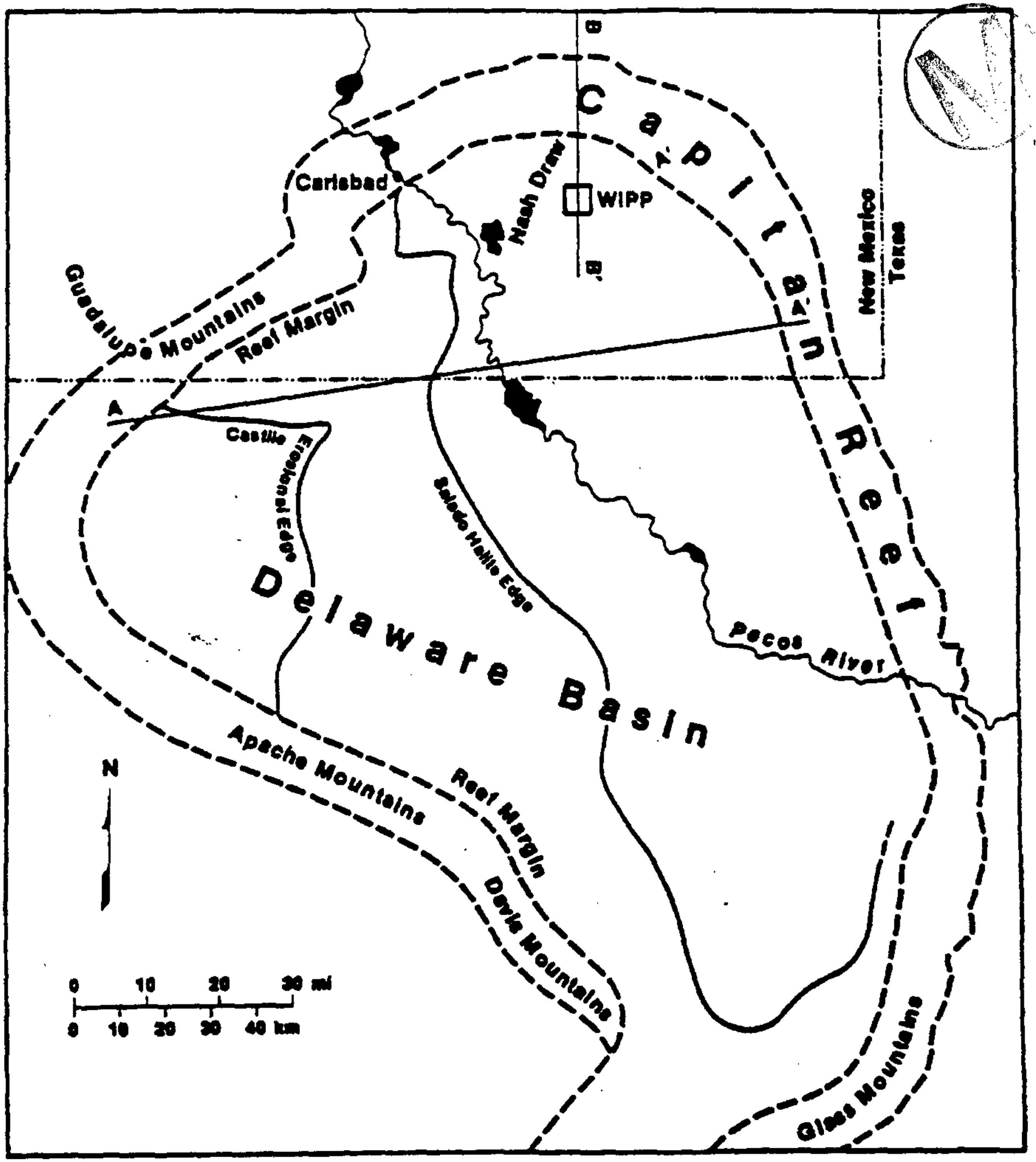


Figure 3-10. Generalized Geology of the Delaware Basin, Showing the Location of the Capitan Reef and the Erosion Limits of the Basinal Formation (from SAND92-0700/2, 1992, after Lappin, 1988).\

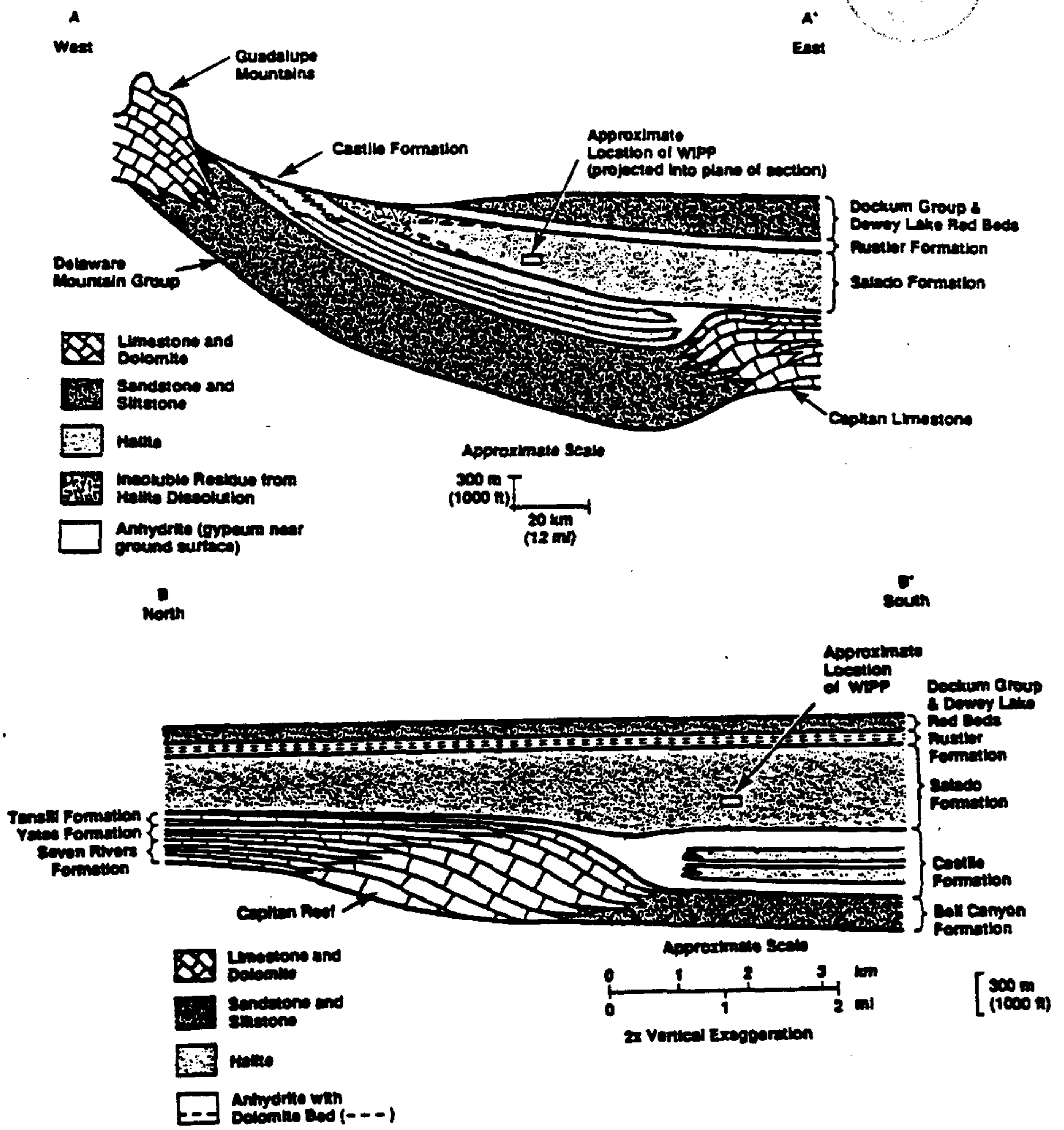
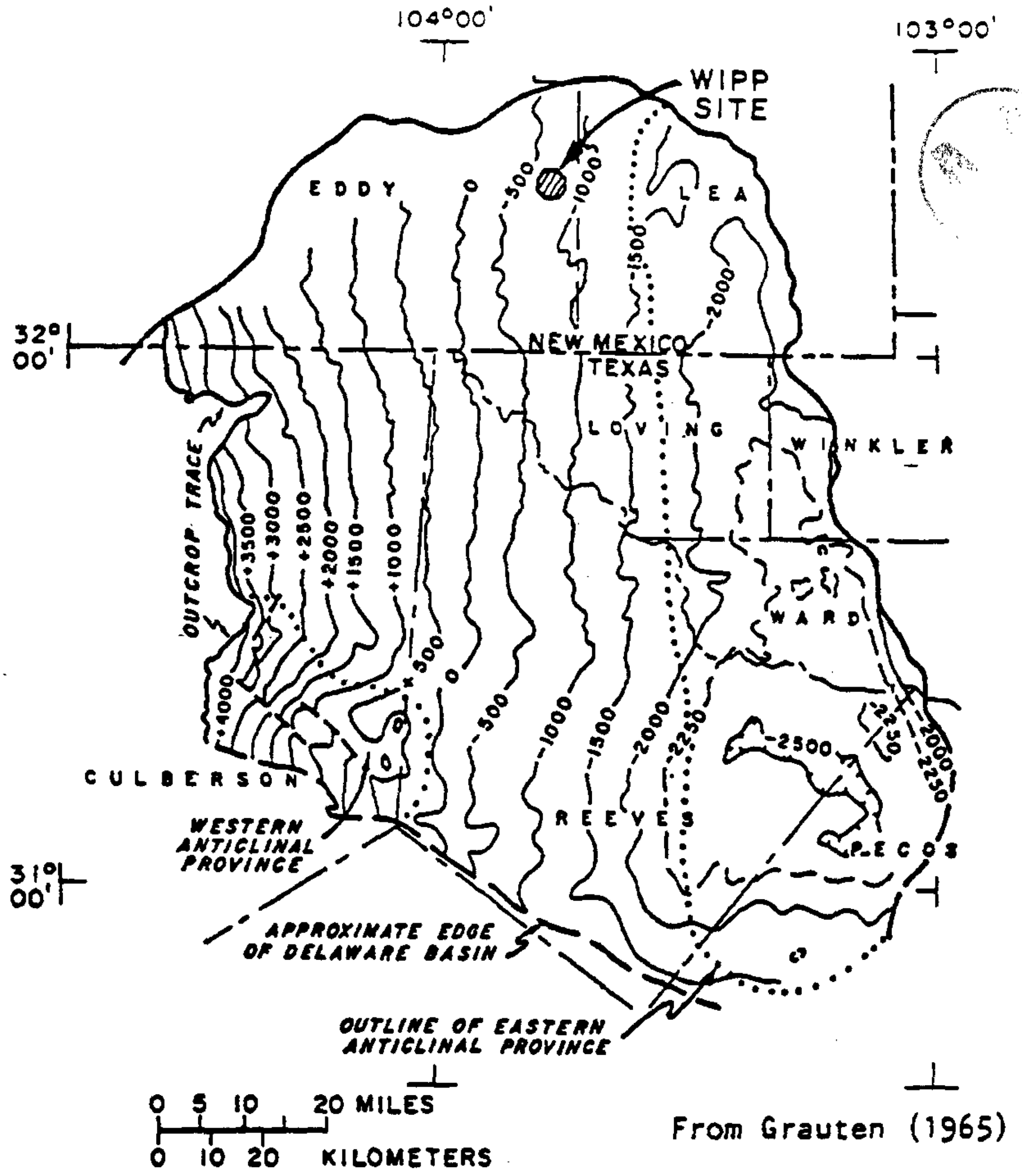


Figure 3-11. Schematic East-West (A-A') and North-South (B-B') Cross-Sections through the Northern Delaware Basin (from SAND92-0700/2, 1993, after Davies, 1984).



From Grauten (1965)

EXPLANATION

1500 STRUCTURE CONTOUR--Shows altitude of top of Delaware Mountain Group. Dashed where approximately located. Contour intervals 250 and 500 feet. Datum is sea level.

Figure 3-12. Generalized Structure Contours on Top of the Lamar Shale of the Bell Canyon Formation (from Mercer, 1983).

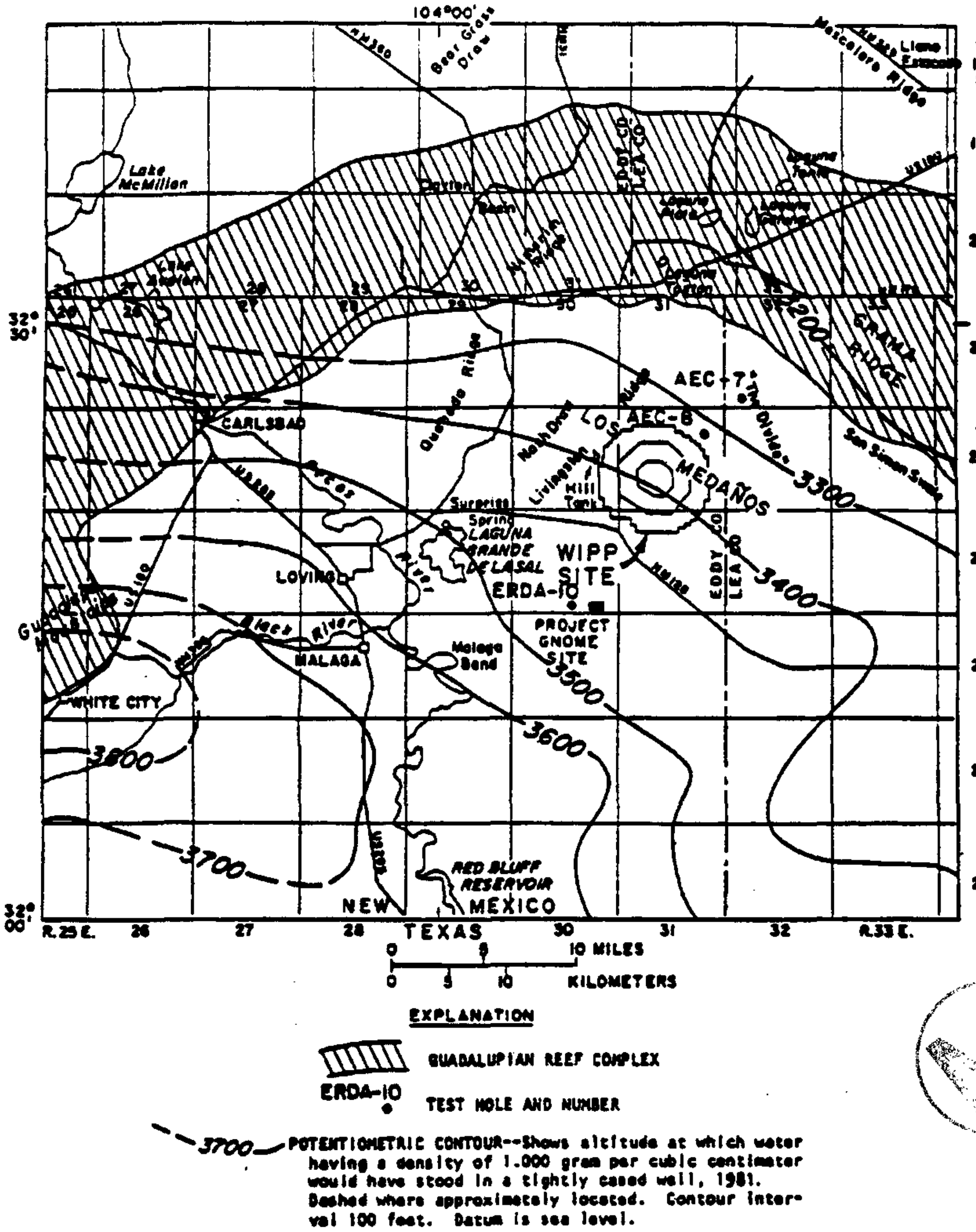


Figure 3-13. Potentiometric Surface of the Hydrologic Unit in the Upper Part of the Bell Canyon Formation (from Mercer, 1983).

slowly moving to the northeast, nearly paralleling the regional structural trend under gradients of 0.005 to 0.008.

It is postulated (SAND92-0700/2, 1992) that responses to regional tectonic adjustments, which gave rise to decreases in the supply of clastic sediments and intermittent connection with the open ocean, resulted in the thick evaporitic sequence of the Ochoan series that covered the Bell Canyon of the Guadalupian series. The Ochoan series are described in order of deposition.

- The Castile Formation consists of thick anhydrite beds with thin interbeds of salt and is of importance to WIPP because it is the first layer below the Salado and contains isolated pockets of pressurized brine and hydrogen sulfide gas in fractured anhydrite beds that have thus far only been found to be associated with structural features. Mercer concludes that these isolated pockets are discontinuous and form no regional flow system within the basin (although localized systems have developed within outcrop areas). He further concludes that the unit acts as a confining layer for water moving in the Bell Canyon below it. The isolated pressurized pockets of brine and gas are of concern because they supply a limited source and driving force for liquids and gas for potential human intrusion scenarios associated with exploratory drilling. This unit has also been of much concern in the past under the "breccia pipe" theory of Anderson (1978, 1981) which postulates development of vertical circulating flow paths in the fractures of this unit that would allow the waters of the Bell Canyon to rise under a density gradient and fall as saturated brines after dissolving the halites of the Salado (Mercer, 1983).
- The Salado Formation has been divided into three stratigraphic units — an Upper Member, the McNutt Potash Zone, and a Lower Member (Figure 3-9) — near WIPP by Jones (1975), in describing the potash resources of the area. It can be differentiated from the Castile because it principally consists of halite in thick interbeds that have been interpreted to be part of repeated multiple bedded sequences (generally on the scale of 0.1 to 1.0 m). These sequences are assumed to be part of a rhythmic fundamental evaporite sedimentation cycle, interpreted by Jones (1973) as an evaporite cyclothem. The cycle starts with deposition of clastic at the base and grades upward through sulfate, halite, and a mixed halite-clastic and then repeats. These beds are generally laterally persistent over large areas, as evidenced by the 45 numbered, anhydrite marker beds 100 through 144 (SAND89-0462, 1989), that are used for stratigraphic control within the vicinity of WIPP by the potash industry. (The 45 numbered interbeds are inconsistent with the 44 in SAND92-0700/2, 1992.)

  While small pockets of brine have been encountered in mining and drilling operations and pockets of nonflammable gases and air have been encountered during the drilling of stratigraphic test holes that have caused blowouts of the drilling fluid, there has been no evidence of flowing water found during the drilling of test holes or during investigations for potash mining. Mercer (1983) indicates that no or very slow natural groundwater flow is suspected to occur in the intact, undisturbed portions of the Salado Formation because there is no evidence of flowing waters and because the slow plastic flow (creep) of the principal formation component (halite) is thought to prevent the maintenance of primary intergranular porosity, solution channels, or open fractures. However, this does not imply that the formation is dry. Brine does seep into the WIPP excavations (brine production rates of 0.01 l/day/m-of-excavation-length have been estimated, as discussed in SAND92-0700/2, 1992).

  Inconsistencies, such as far-field pore pressure measurements that are not in equilibrium (Section 4.2) and which imply flow from the more permeable anhydrites to the less permeable Salado may have led Guzowski (1990) to conclude that sufficient data are not currently available to determine the natural pattern of groundwater flow in the Salado, if it does exist (SAND92- 0700/2). Gathering sufficient information to resolve some of these inconsistencies completely is complicated by what might be described as the nemesis of geologic disposal (i.e., the "best natural systems" for containment and slow release are the "most difficult to characterize").

Measurement generally requires emplacing probes to measure responses to a disturbance propagated over the spatial measurement scale of interest (e.g., by injecting a fluid) and then observing the response of the system as it returns to equilibrium. However, the long time required for perturbations to propagate in low permeability formations (generally considered the best for waste isolation) restricts such measurements to a small spatial scale with questionable relevance to repository performance. Additionally, when measurements are made at these small scales, the volumes of rock disturbed by emplacement of measurement probes and perturbation (e.g., injection) holes, and the volumes and properties of the probes become significant relative to the volume of undisturbed rock; thus increasing the uncertainty and biasing of the measurement.

An additional issue and source of uncertainty is related to the validity of the assumption that Darcy's law governs the flow of fluids in the halites of the Salado, (as is discussed in more detail in Subsection 4.2). It is apparent that full resolution of the above issues (e.g., removal of all measurement bias, reduction of measurement uncertainty, determination of exactly the conditions for transition from Darcy to non-Darcy flow) is neither possible nor necessary to demonstrate that there is a reasonable expectation of compliance. Since determining what can and needs to be done to demonstrate compliance can be a difficult and controversial process, it would seem that a more formal method is required that attempts to assess realistically what can be achieved in an appropriate time frame and for an appropriate cost; (see Section 3.2).

- The Rustler Formation (discussed in more detail in Subsection 4.3) is described by Mercer (1983) as the youngest of the Ochoan evaporite sequence containing the most transmissive units above the Salado, as illustrated in the hydrostratigraphic column in Figure 3-14. The Magenta and Culebra are dolomites, and the others (unnamed, Tamarisk, and Forty-Niner) consist of differing amounts of anhydrite, siltstone, claystone, and halite (SAND89-0462, 1989). Of these, the Culebra dolomite is the most laterally continuous and productive unit in the vicinity of WIPP; however its waters, which vary from saline to briny, are of little use because of the marginal quality and variability in the yields (Mercer, 1983). The conceptual model for regional flow in these units is dependent on other regional setting factors and is discussed in subsequent paragraphs.
- The Dewey Lake Redbeds (discussed in more detail in Subsection 4.4) are the uppermost unit of the Ochoan Series and the last of the Permian System rocks. They consist largely of siltstones and claystones that serve to buffer recharge from above because of their low permeability (SAND89-0462, 1989).

The Culebra dolomite of the Rustler Formation (a secondary natural barrier at WIPP) is an important part of the hydrologic system that exists in the supra-Salado sediments (above the Salado) in the vicinity of WIPP. In addition to the Culebra dolomite, the other more permeable and areally extensive units of this hydrologic system (Figure 3-14) include the Magenta dolomite, which has nearly the same areal extent as the Culebra, and the "brine aquifer," which is of limited extent and is located in the dissolution residuum of the Rustler-Salado contact zone in Nash Draw (Figure 3-15). The influence of near-surface dissolution of the evaporites is apparent in the topography of the area (Figures 3-16 and 3-17), which gently rises to the topographic high of the "caprock" of the Llano Estacado along Mescalero

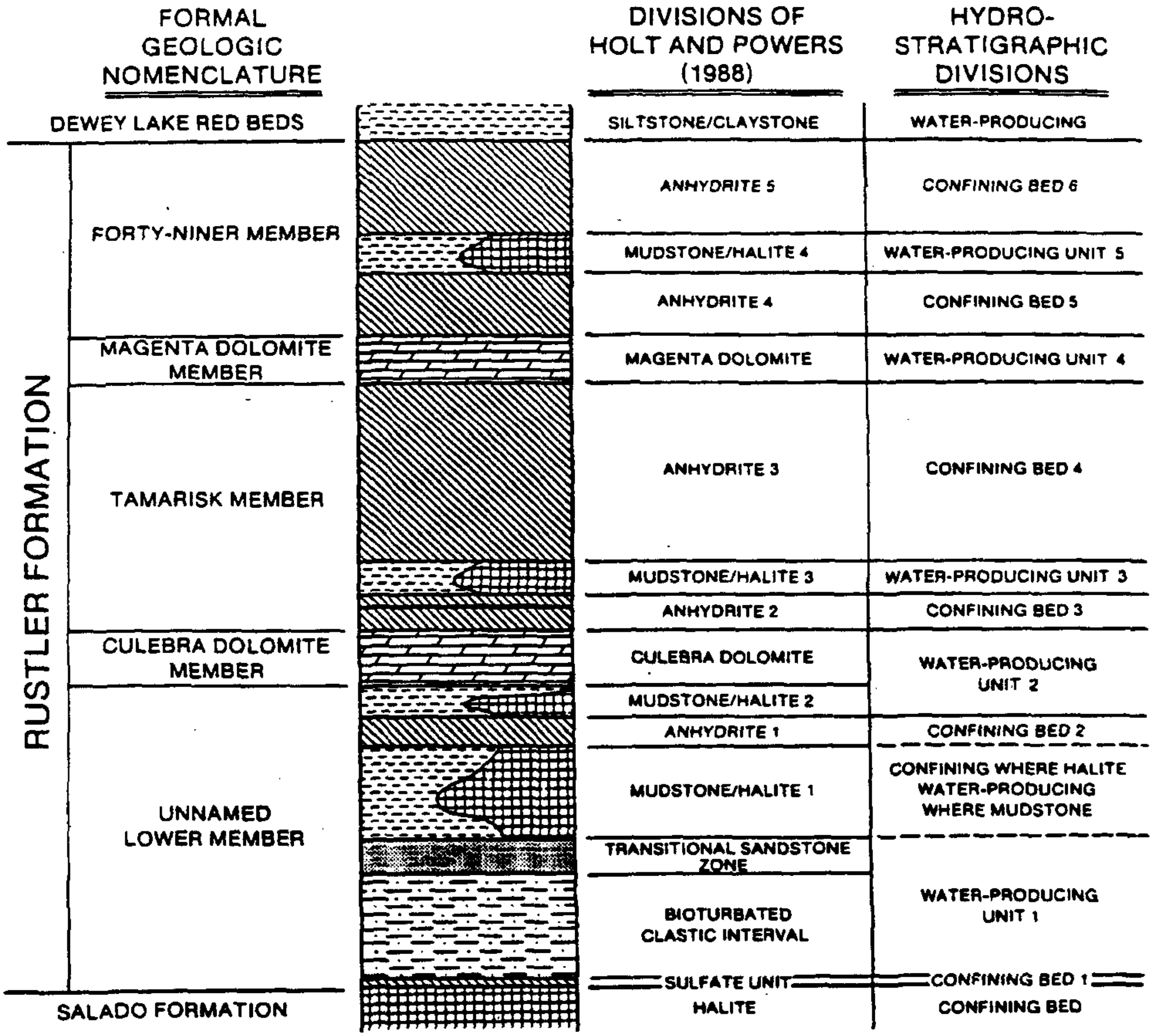
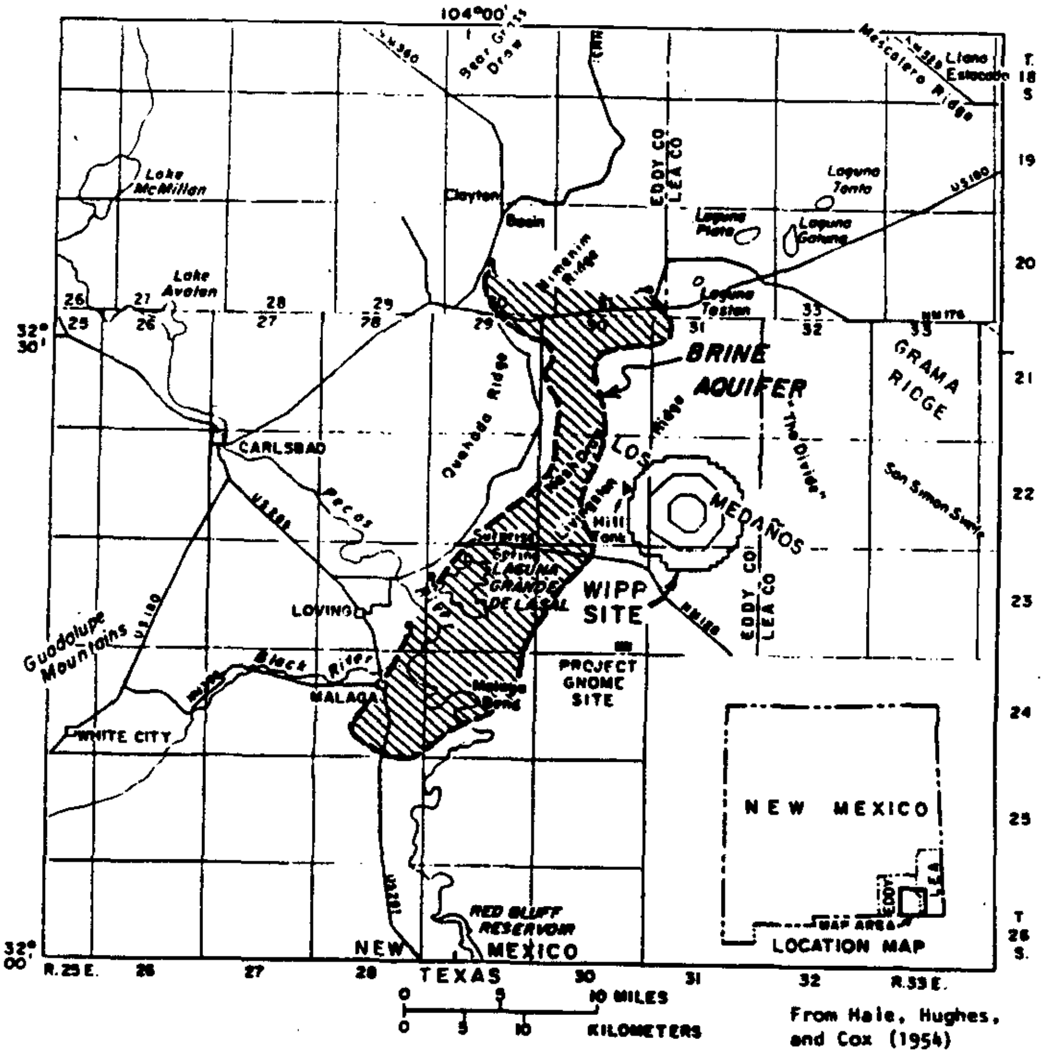


Figure 3-14. Hydrostratigraphic Column of the Rustler Near the WIPP Site (Beauheim and Holt 1990).



From Hale, Hughes, and Cox (1954)

Figure 3-15. Approximate Extent of the "Brine Aquifer" Near WIPP (from Mercer, 1983).

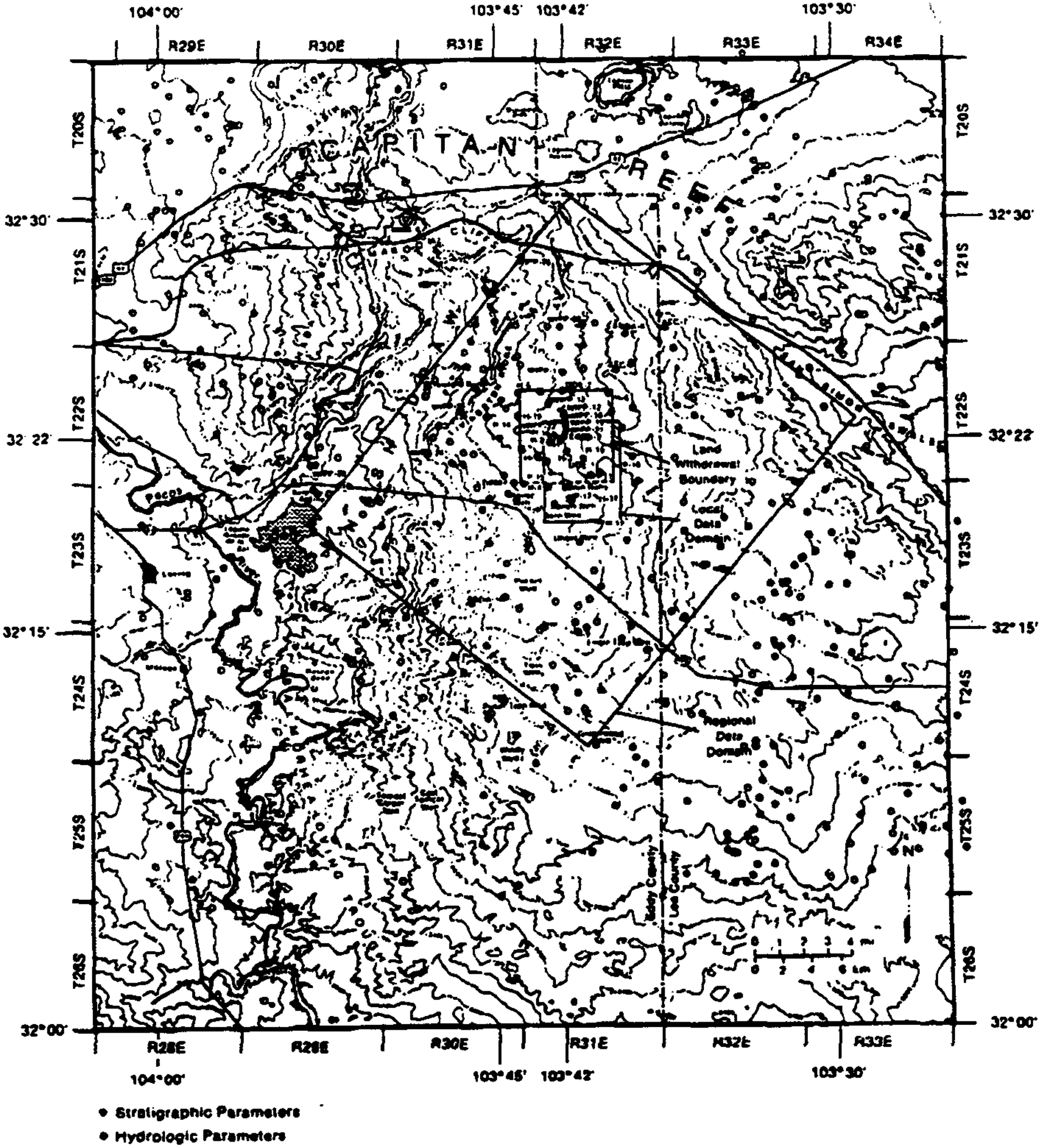


Figure 3-16. Topography of the WIPP Area, Locations of Wells for Defining General Stratigraphy, and the Regional and Local Data Domains Used in the WIPP PA (SAND92-0700/3, 1992).

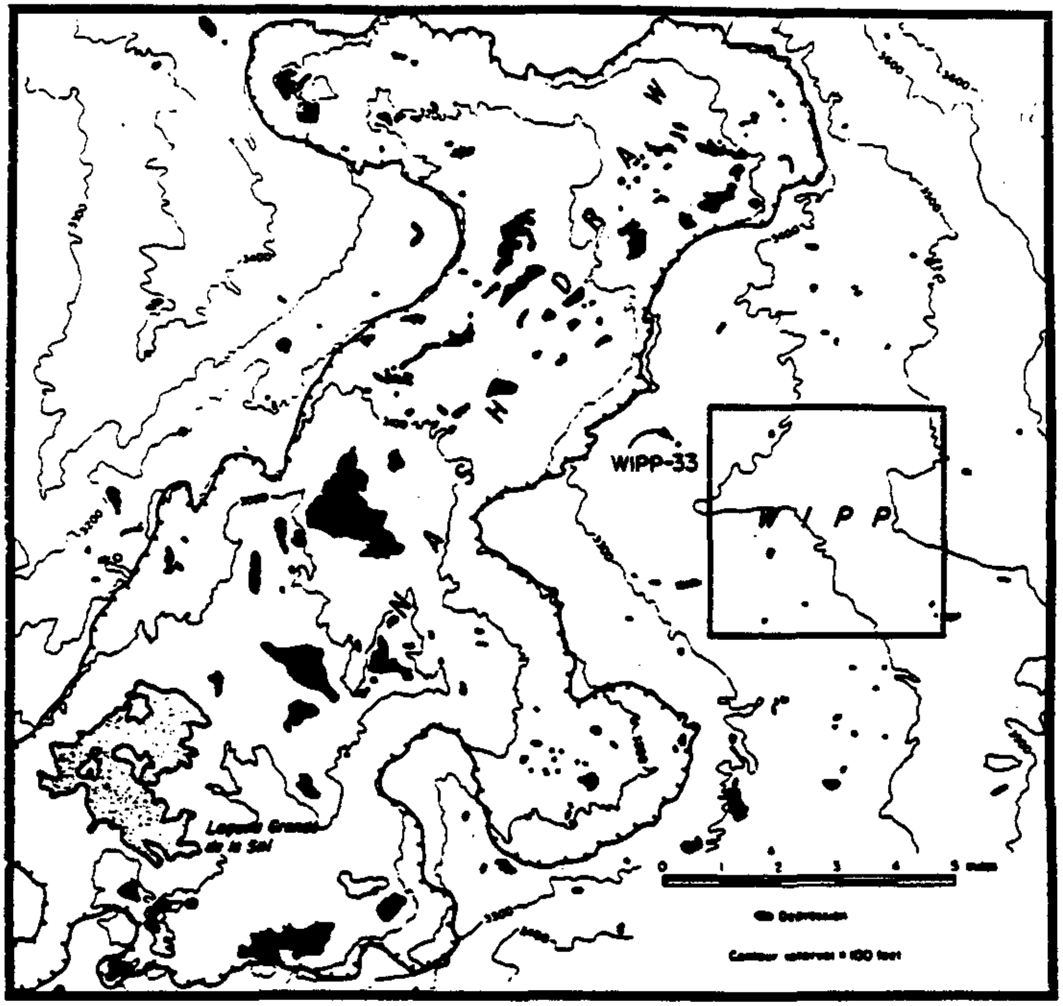


Figure 3-17. Topography Contours (100 ft interval) for the General Area Around the WIPP Site and Nash Draw, Showing Areas of Closed Topographic Depressions and the Location of WIPP 33 (from Chaturvedi and Channell, 1985).

Ridge (Figure 3-15) as one proceeds to the east and north from the Pecos River to the south, and the depressions associated with the three nearest karst dissolution features: the Balmorhea-Loving Trough to the south of WIPP, Nash Draw to the west , and Clayton Basin to the northwest (Mercer, 1983; Chaturvedi and Channell, 1985; SAND92-0700/2). The topography also gently rises as one proceeds to the west and north from the Pecos River, Nash Draw, and the Clayton Basin (Figures 3-16 and 3-17). The area is covered with sand dunes (which can enhance infiltration and thus recharge) and is vegetated with mesquite, scrub oak, and other typical northern Chihuahuan desert plants that exist with the 28-34 cm/yr of precipitation (which is dominated by a late summer monsoon) and the 17.1°C average annual temperature that gives rise to a surface water or pan evaporation of 280 cm/yr (Mercer, 1983; SAND92-0700/2).

Development of a conceptual model for flow in this supra-Salado hydrologic system is complicated by a variety of interpretational issues.

- There is a potential for the various members of the Salado and supra-Salado Formations (Bachman, 1980 and 1985; Snyder, 1985; Chaturvedi and Channell, 1985; Lowenstein, 1987; Holt and Powers, 1988) to
  - dissolve (e.g., the halites, dolomites, and gypsum) and form solution cavities and channels/conduits (e.g., WIPP 33, Figure 3-17) or to give rise to more rapid removal of unit as related to their average proximity to recharge sources from the surface through time (**Figures 3-18 and 3-19**),
  - subsequently slump and fracture harder units (e.g., the anhydrites and dolomites), and
  - convert anhydrite to gypsum (with the associated expansion, fracturing, and sealing capabilities) which itself eventually dissolves as a result of the movement of circulating groundwaters (**Figure 3-20**).

  In the words of Snyder (1985), there is a potential for a member unit to "feed upon itself" and alter its own geohydrologic and geochemical properties in response to fresh (or low TDS) water circulating from recharge sources to discharge locations.
- There is the associated difficulty and debate (Bachman, 1980 and 1985; Snyder, 1985; Chaturvedi and Channell, 1985; Lowenstein, 1987; Holt and Powers, 1988; SAND92-0700/2) surrounding conclusive determination of the origin, timing, and locations of syndepositional versus post-burial dissolution zones, and the current status of any dissolutioning or alteration that has taken (or is taking) place within the Rustler.
- It is not possible to relate observations of hydrochemical facies (**Figure 3-21**) to current flow patterns inferred from adjusted potentiometric contours in these variable fluid density geohydrologic systems because these systems may be in a transient state that is out of equilibrium with both current and past climatic/recharge conditions. (**Figures 3-22, 3-23**, and **3-24** are the adjusted potentiometric contours for the Rustler-Salado contact zone, Culebra dolomite, and Magenta dolomite respectively.)
- There are difficulties associated with characterizing low permeability and heterogeneous geohydrologic systems because the support volume associated with any of the measurements is very small (the nemesis of geologic disposal discussed earlier).

The limited review of the data and abundant literature on the supra-Salado geohydrologic system in the vicinity of WIPP suggests the possibility of using a Toth type of local topographic-driven conceptual model for the periods of more humid climate during Gatuna time (**Figure 3-25**; SAND92-0700, 1992),

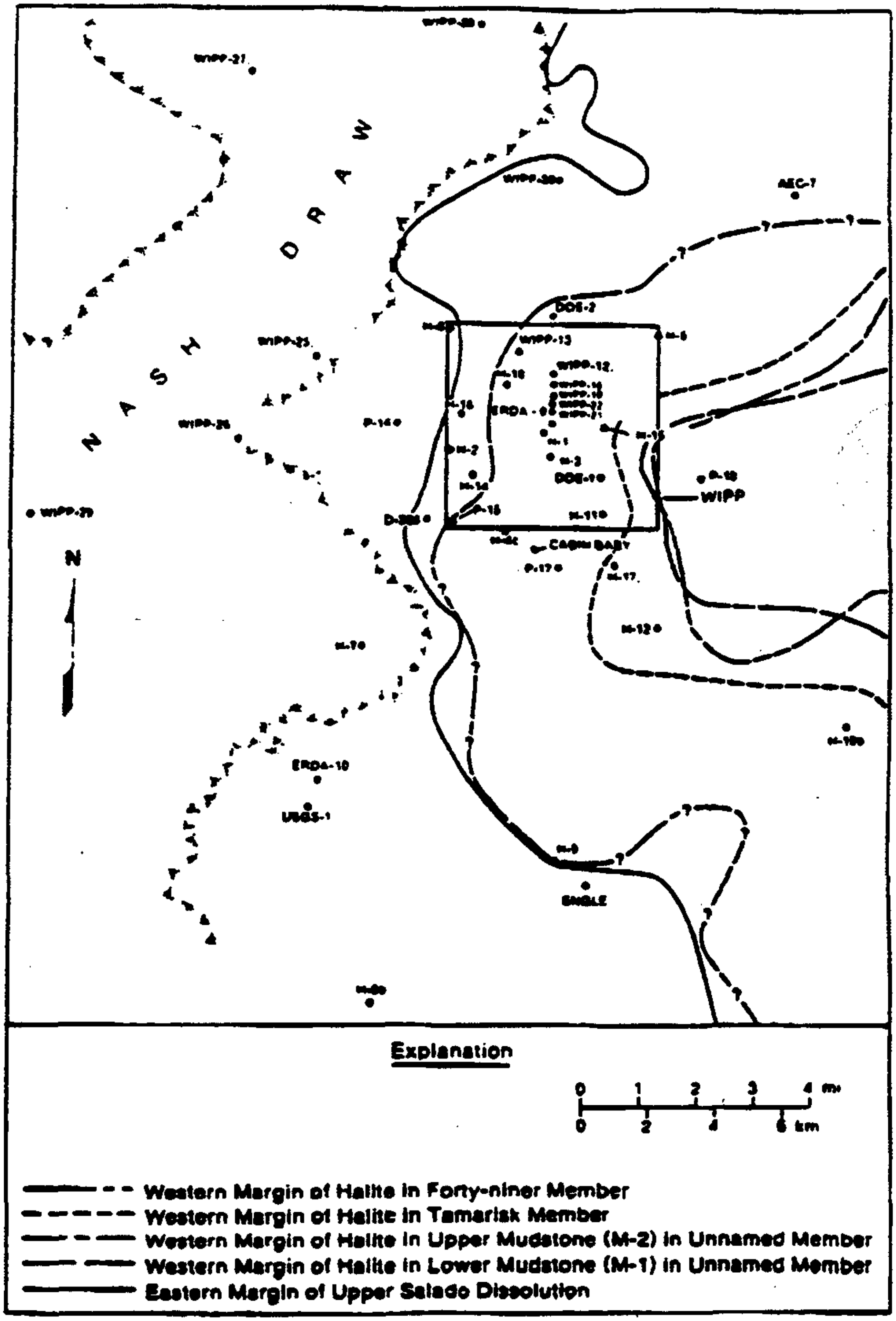


Figure 3-18. Eastern Margin of Upper Salado Dissolution and Western Margins of Rustler Formation Halite Around WIPP (reproduced out of SAND92-0700/2 from Lappin et al. 1989).

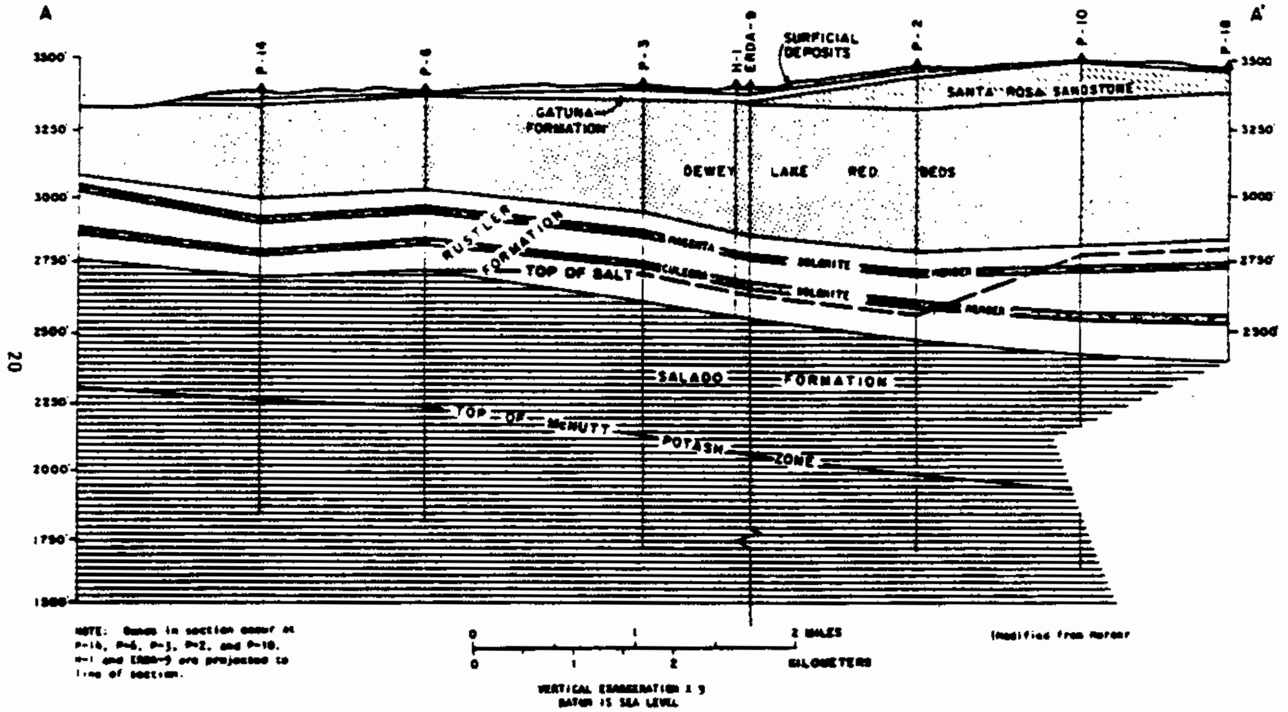


Figure 3-19. Geologic Section Across the WIPP Site Showing Approximate Location of Salt in the Rustler (from Mercer, 1983).

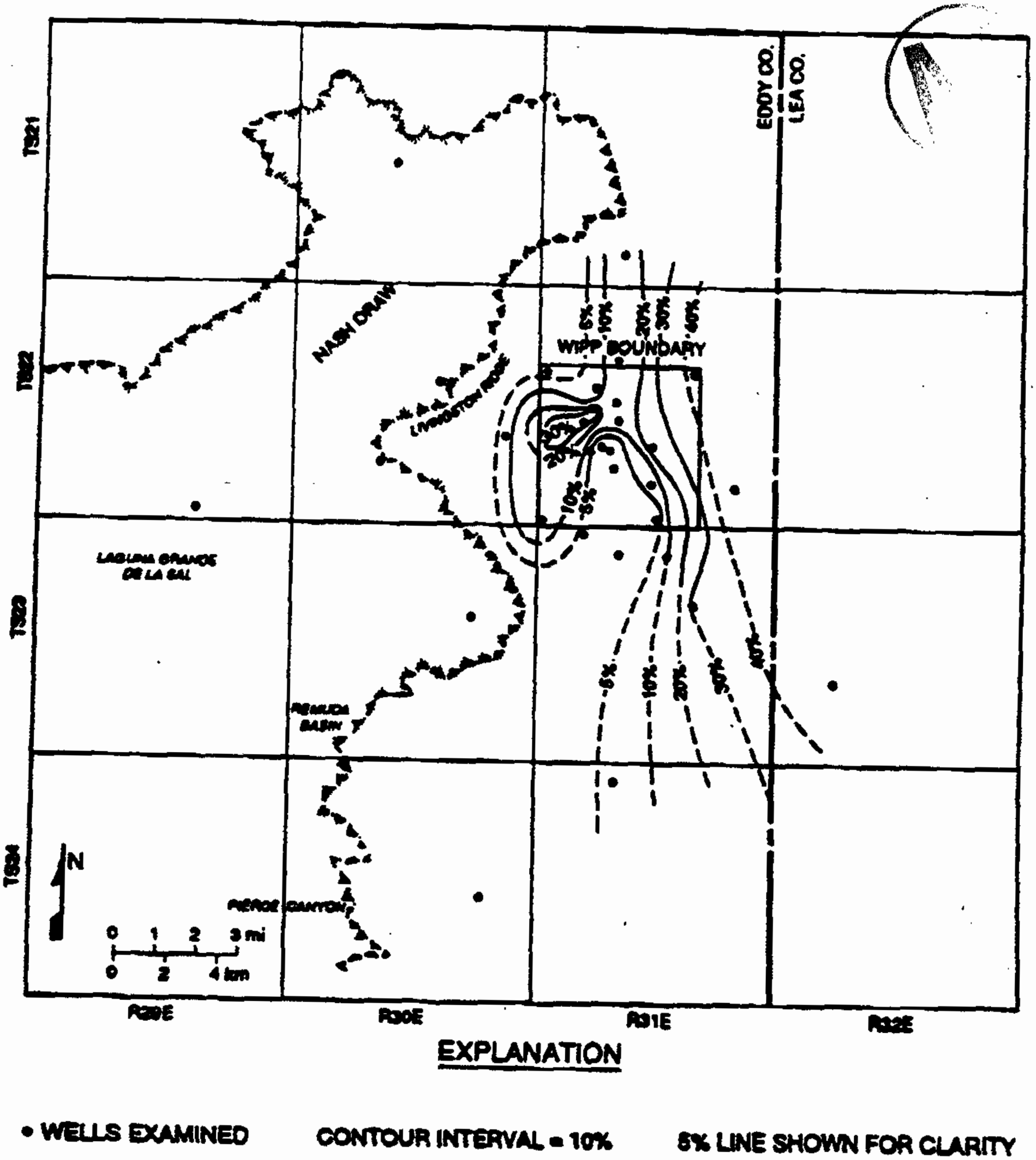


Figure 3-28. Percentage of Natural Fractures in the Culebra Dolomite Member Filled with Gypsum (reproduced from SAND92-0700/2, 1992, after Beauheim and Holt, 1990).

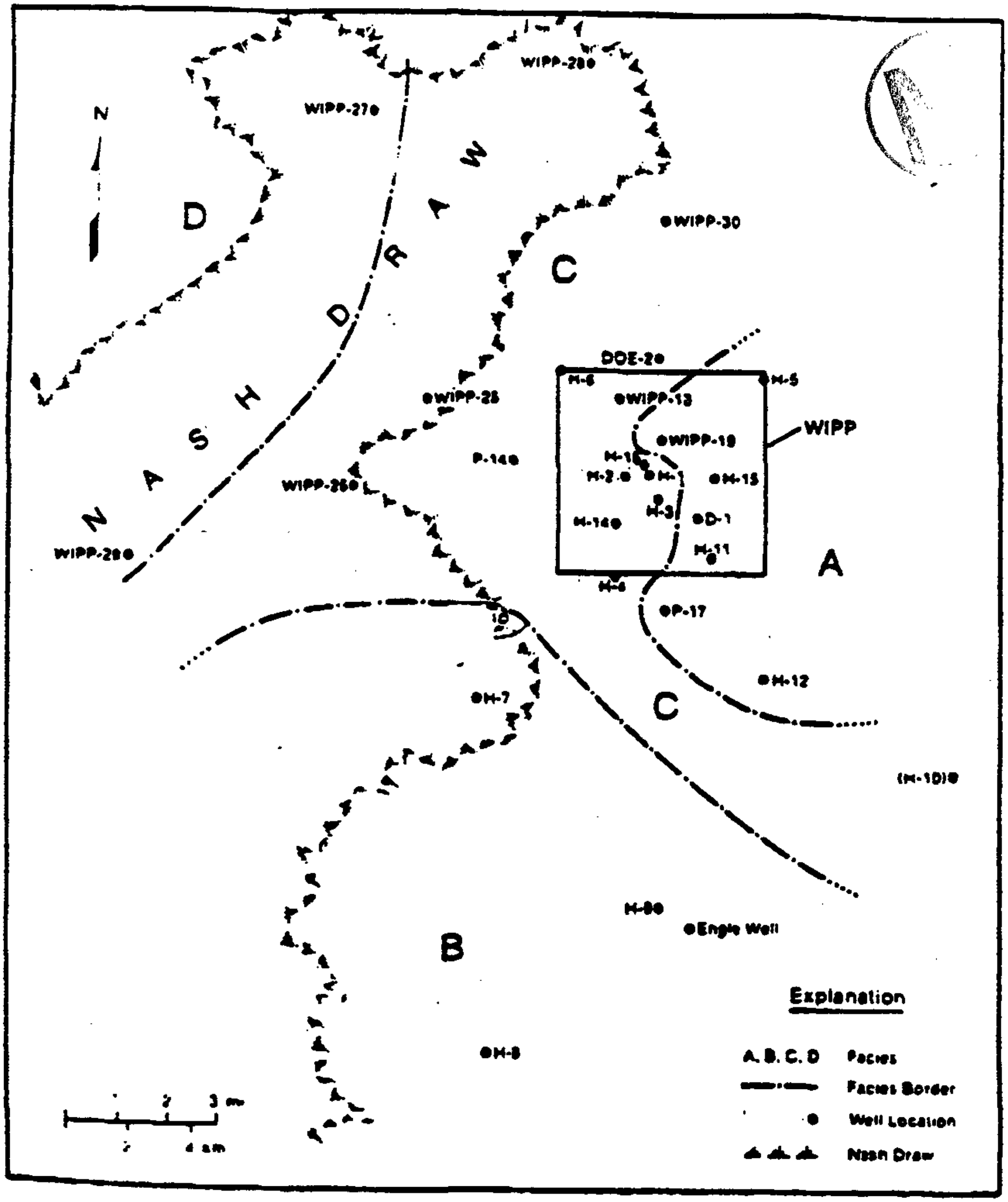


Figure 3-21. Hydrochemical Facies in the Culebra Dolomite Member of the Rustler Formation (reproduced from SAND92-0700/2, 1992, after Siege et al. 1991).

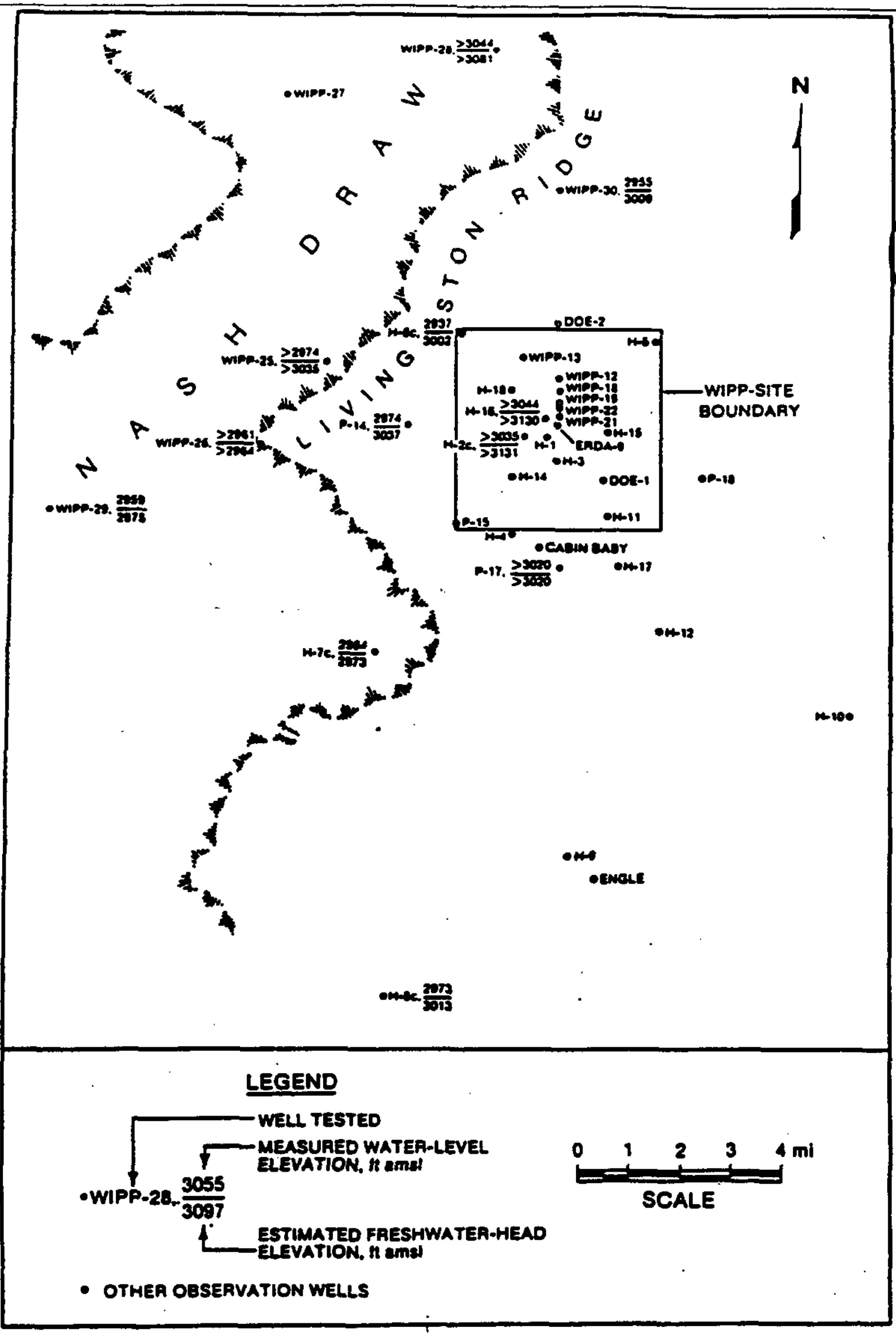


Figure 3-22. Measured Water Level and Estimated Freshwater Head Elevation of the Unnamed Lower Member of the Rustler and/or Residuum along the Rustler/Salado Contact (from Holt et al., 1989)

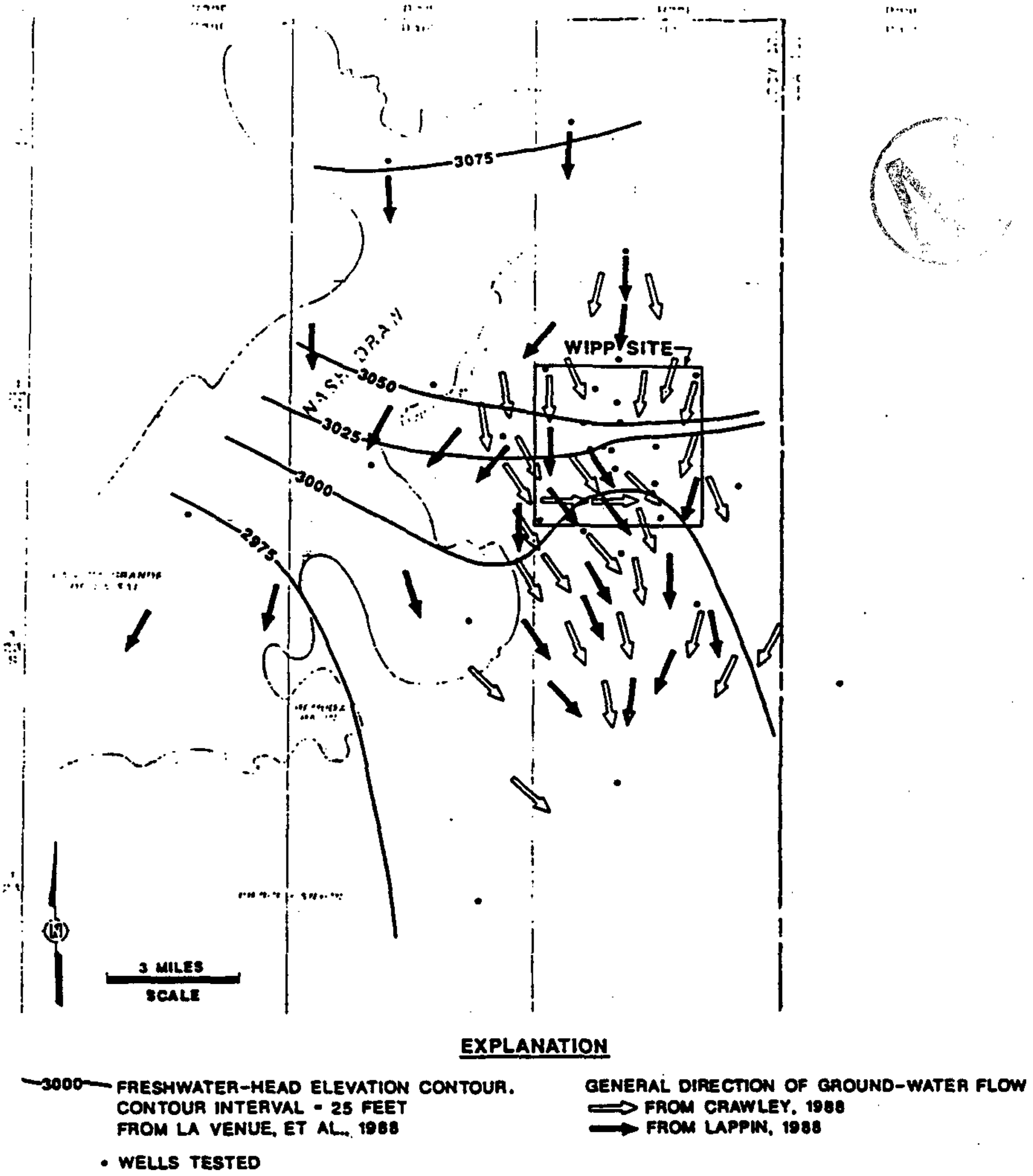


Figure 3-23. **Estimated Culebra Dolomite Member Freshwater Heads and Flow Directions (from Holt et al., 1989).**

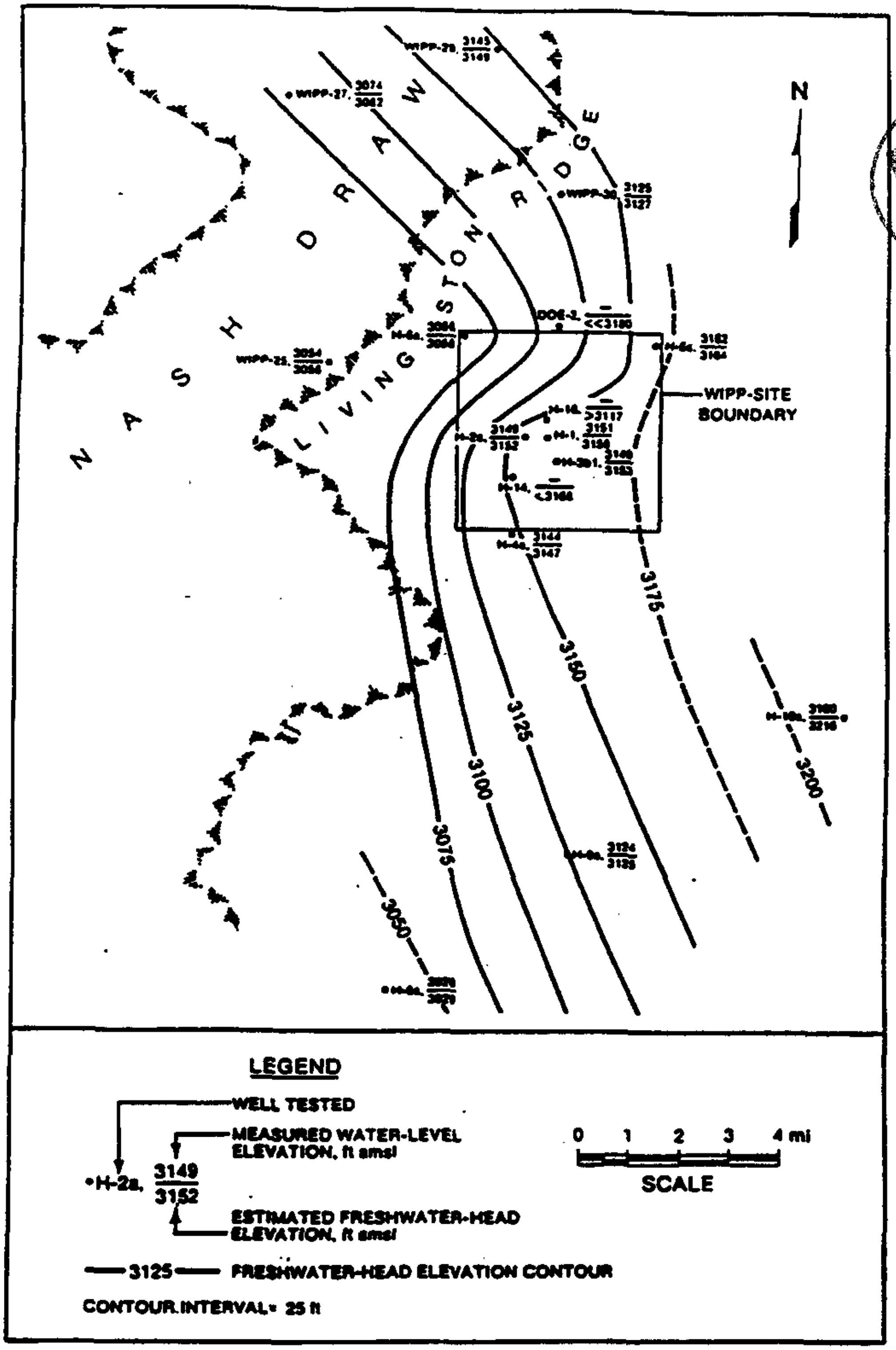


Figure 3-24. Measured Water Level and Estimated Freshwater Head Elevation, Magenta Dolomite Member (from Holt et al., 1989).

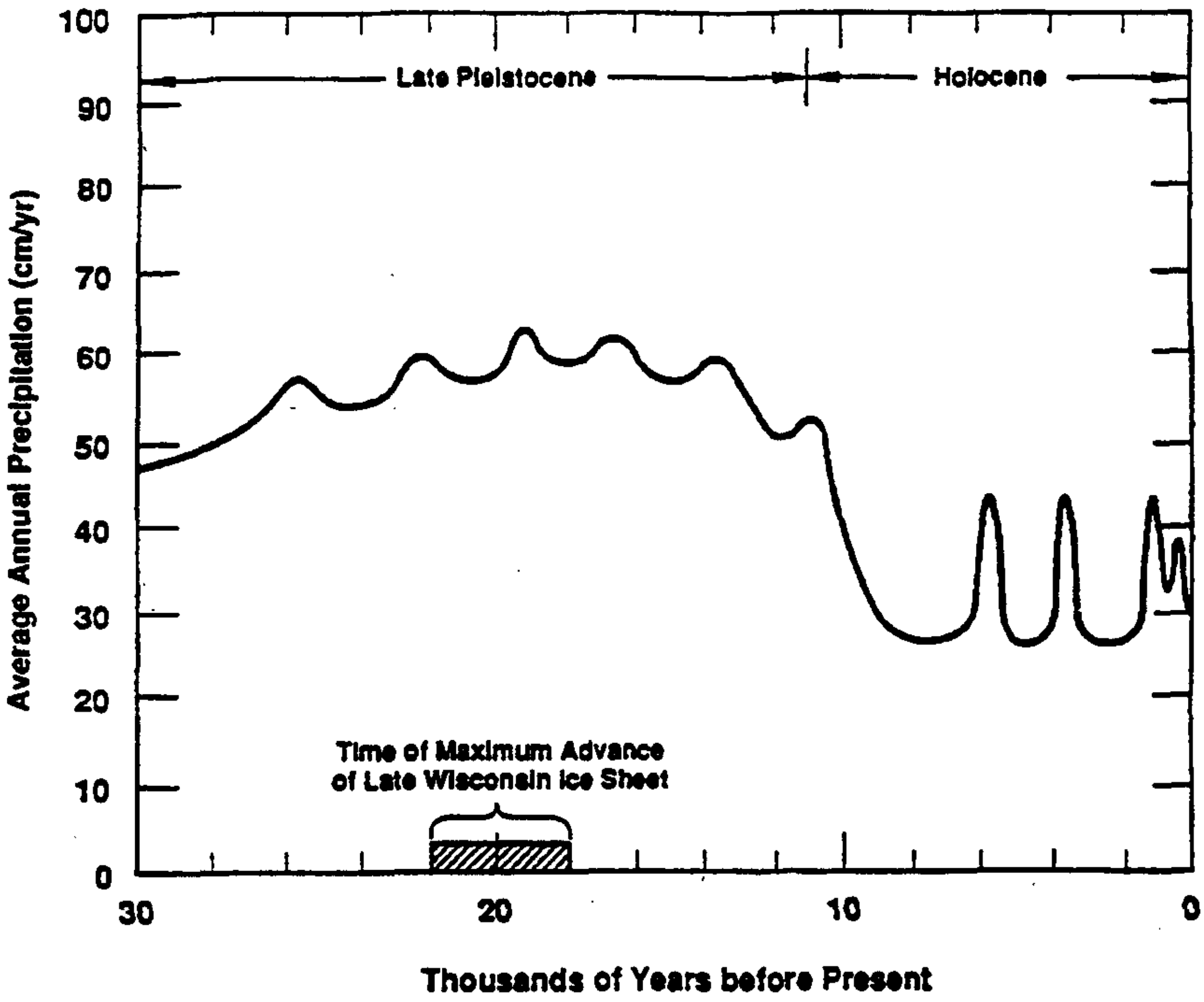


Figure 3-25. **Estimated Mean Annual Precipitation at the WIPP during the Late Pleistocene and Holocene (reproduced from SAND92-0700/2, 1992, as modified from Swift, 1992).**

when surface streams (**Figure 3-26**) were postulated to exist in the vicinity of WIPP (Bachman. 1985), and a change to larger intermediate or more regional circulation during the dry periods. During periods of greater precipitation, higher and more uniformly distributed recharge moved through the supra-Rustler sediments (e.g., the 10^{-8} m/s hydraulic conductivity of the Dewey Lake Redbeds could allow up to 30 cm/yr to infiltrate under unit gradient conditions of unsaturated flow) and a higher water table, whose contours would probably have mimicked some subdued version of the local topography. Recharge would move vertically downward and then laterally, where it would discharge to both local and more regional surface water drainages. Hydrologic systems, during these humid times, circulate more and fresher (i.e., lower TDS) groundwaters. As a result, most of the post-burial (and not syndepositional) dissolutioning and alteration of the Rustler (Figure 3-18 and 3-20) took place during these times, since observed patterns of halite removal and hydrochemical facies dissolution (Figures 3-18 and 3-21) are more consistent with directions of flow inferred from a subdued version of the topography. These periods of more humid climate may have been followed by dryer climate periods (Figure 3-25) that would result in very low or potentially spotty recharge through the supra-Rustler sediment, such as proposed by Mercer, (1983) for the Dewey Lake, or through the runoff to closed depressions (Figure 3-17), and subsequent deep infiltration as proposed by Chaturvedi and Channell (1985). Under this model, the low flows of the dry periods would cause the flow directions of the higher permeability units (e.g., the Culebra) to change more rapidly in response to the change in recharge locations and quantities, as proposed by Siegel and Lambert (1991) and discussed in SAND92-0700/2 (1992).

The reasonableness of local recharge can be demonstrated by simple hand calculations of flow through the Culebra, since it probably carries the majority of the flow. These calculations of flow and recharge are based on the following:

gradient = 0.003 (from 932 m and 914 m contour along east side of WIPP, Figure 3-23);
mean thickness = 7 m (SAND92-0700/2);
width = 20 km (distance from southeastern corner of WIPP site to eastern edge of Figure 3-23);
K = 10^{-4} m/s to 2×10^{-10} m/s (hydraulic conductivity, SAND92-0700/2);
flow estimate = 0.4 m^3/s to 8×10^{-7} m^3/s (compare this to the 0.91 m^3/s estimated to recharge the Pecos River from stream gage data, SAND92-0700/2, 1992).

The calculations translate to a uniformly distributed recharge equivalent (if presumed to all take place in the 20-km-by-20-km (12-mi-by-12-mi) area in the upper left corner of Figure 3-24) that ranges from a minimum of 7×10^{-6} cm/yr to a maximum of 3 cm/yr *[i.e., $0.42\times3.15\times10^{7}\times100/(20{,}000\times20{,}000)$]*. It should be noted that the high estimate is still only 0.1 of annual rainfall and that even this maximum recharge estimate would only require a saturated hydraulic conductivity of approximately 10^{-8} m/s under unit gradient conditions. To support this conceptual model further, hand calculations could be carried out to estimate the potential volume of halite that could have been dissolved, and deterministic modeling could be undertaken to test various aspects of this conceptual model that would lead to the selection of the appropriate model for compliance calculations.

These discussions of a Toth-type conceptual model for the supra-Rustler hydrologic system were presented to raise several issues, discussed below, that PART believes are important to the WIPP development of a PA document and documentation trail adequate for licensing decisions.

- **Conceptual Model Documentation and Assumption Justification.** The current PA (SAND92-0700/1-3, 1992) provides no coherent presentation of the plausible conceptual

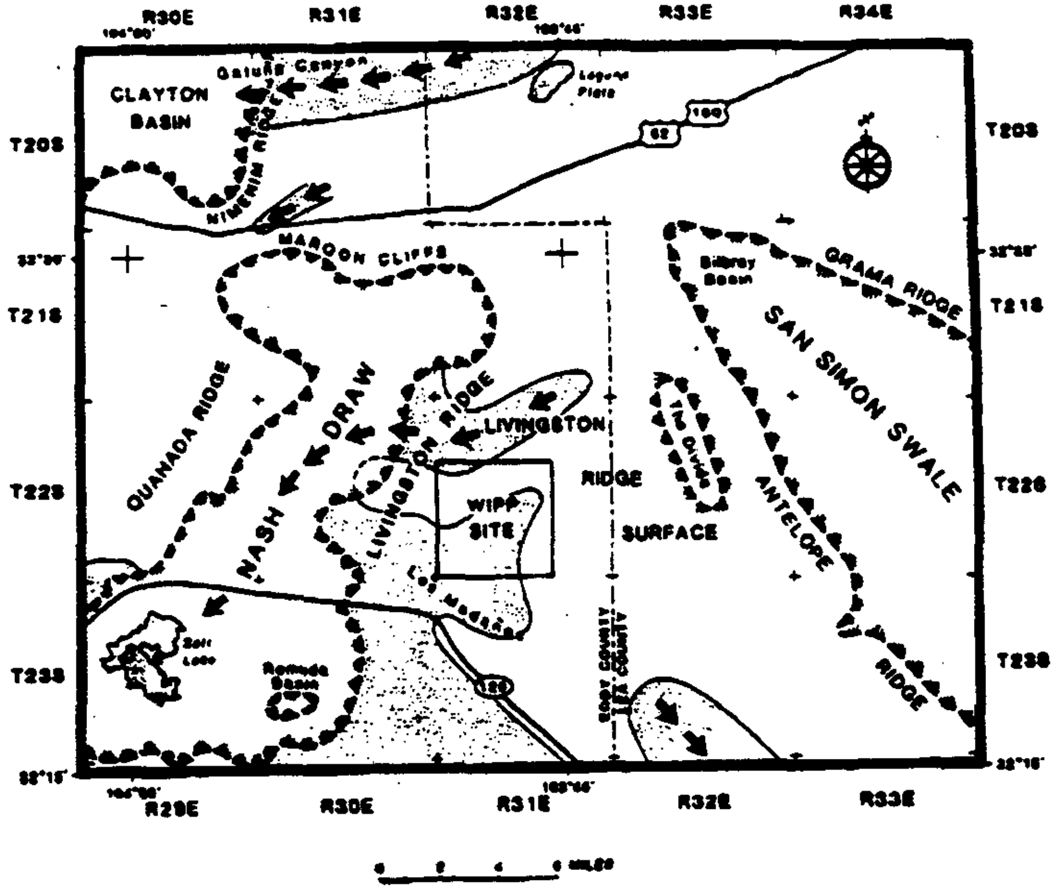


Figure 3-26. **Distribution of Gatuna Formation in the Vicinity of WIPP (stippled) and Probable Course of Streams During Gatuna Time (arrows) (reproduced from Bachman, 1985).**

model(s) for the supra-Salado hydrologic system in the vicinity of WIPP. This is a significant issue because the interpretation of measurements and observations, as well as the selection of an appropriate way to model the Culebra, is dependent on an understanding of the supra-Salado hydrologic system conceptual model. The PA must contain a coherent discussion of the(se) model(s) in order to address the major interpretational issues discussed above and to properly discuss and document the Culebra conceptual model and justify the various associated assumptions. The Culebra conceptual model and major assumptions are discussed in some detail within the current PA, although evidence is not generally presented to justify/support them; (see Subsection 4.3 for PART's detailed discussions of the Culebra).

For example the PA discusses pressure measurements at four wells that indicate upward flow from the Magenta and the claystone unit of the Forty-Niner and concludes: "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." The context (i.e., the supra-Salado hydrologic system conceptual model assumptions) for this interpretation is not discussed, and the reader wonders how this low permeability clay unit came to be under-pressurized when the logic offered for the lowered pressure in the Culebra (relative to the pressure in the lower conductivity Magenta) was that faster drainage occurred because of its higher conductivity. The reader wonders what zero recharge means. Are these formations so tight that recharge through them is zero and yet the halite disappears? Or, does this conceptual model require the Holt and Powers (1988) assumption of syndepositional distribution of halite?

This same evidence (i.e., Magenta to claystone pressure comparisons at four wells - DOE-2, H-3, H-14, and H-16 - which actually showed upward gradients, with one highly uncertain downward gradient at DOE-2, Beauheim, 1987) would be interpreted quite differently based on the hypothetical Toth-type conceptual model for the supra-Salado hydrologic system discussed above. First, only spotty recharge zones would be expected and these would be located in places where enhanced infiltration is more likely (e.g., closed contours like those at WIPP-33, where surface runoff from high intensity storms could accumulate, and near sand dunes where recharge is at a maximum even in arid environments).

Second, these lower permeability water bearing units of the Rustler (Figure 3-14) could be expected to be out of equilibrium with the higher permeability water bearing units (e.g., Magenta and Culebra), as previously discussed, and yet these higher permeability water bearing units could still be in vertical communication with each other through these spotty recharge windows.

Lappin (1989) discusses some modeling efforts (Haug et al. 1987; Davies, 1989) that suggest that this current PA modeling assumption of no vertical communication needs to be investigated, and it now seems, as discussed earlier in this section, that SNL PIs are investigating a regional hydrologic model of WIPP that examines vertical recharge from the surface through time and includes the various members of the supra-Salado hydrologic system.

Finally, as with all the issues, there is the problem of determining what is sufficient for closure from a compliance-based perspective. What level of realism must be achieved in developing and demonstrating the credibility of the supra-Salado hydrologic system conceptual model and its basic assumptions?

- **Hand Calculations and Supportive Modeling.** As discussed and simply demonstrated for the hypothetical Toth conceptual model, hand calculations can be used to demonstrate the reasonableness of assumptions and should be presented in the PA. The PART performed many hand calculations as part of this review. A progression of simple deterministic or stochastic models is typically investigated as part of the process of examining and justifying the various conceptual model assumptions, and additional modeling analysis is performed to determine the appropriate level of model for compliance analysis. This progression needs to be clearly documented as part of the PA.

These hand calculations, along with brief documentation of the results of this progression of simpler modeling efforts used to justify assumptions, will clearly help achieve those qualitative features of "reasonable degree of certainty" and "reasonable expectation." It is also important to justify and document the analyses that lead to the model selected for compliance, especially when it appears to leave out important processes (see Subsection 5.1.5).

- **Documentation of Issues** ***(Especially Resolved Past Issues)***. During the PART review efforts, a variety of important past issues were encountered in the literature. From the chronology of the documents in the literature, it seems as if they were resolved; (e.g., many documents appear regarding an issue, and then no more articles appear). However, the status and resolution of most of these issues were never discovered in the course of this limited PART review. Furthermore, many of these were never alluded to in the current PA documents, and it is likely that future reviewers will encounter the same difficulties unless some methodical way to document these issues and their resolution status is provided. These issues may have been adequately resolved, but there is less credibility when both the issue and its resolution, or lack thereof, are not transparent. An important example is the whole series of issues and controversies regarding the regional dissolution in the Rustler Formation, many of which are summarized in LaVenue et al. (1990). Relevant issues that arose in the course of this review include the following:
  - Why are there no estimates of the rate of advance from west to east of the Rustler dissolution front?
  - How important is a good understanding of the regional dissolution process(es) to the interpretation of the current groundwater flow system and the predicted possible state(s) over the next 10,000 years? Is it necessary to resolve the controversy regarding syndepositional versus post-depositional dissolution of the halites?

  In order to achieve those qualities of "reasonable degree of certainty" and "reasonable expectation," there is a need to document these issues and their status of resolution through a series of issue resolution documents to aid both the licensing reviewers and any other interested parties. The PA should contain a brief summary of the major resolved and unresolved issues and provide a reference to these issue resolution documents. These documents need to identify and define the issue; identify and summarize the chronology of literature, workshops, and important meetings; summarize the method of resolution; and document the consensus and any dissent. These documents should be prepared under strict QA, with appropriate documented external review by qualified experts.

- **Compliance-Based Issue Resolution**. What must be known and resolved in order to reach compliance is an overriding and difficult issue. Without clearly understanding each issue, getting agreement on its definition, and determining what needs to be known and how well, DOE cannot proceed to the next steps. These involve determining
  - what can be done to demonstrate compliance and how well;
  - what needs to be done; and, finally,

- how closure or resolution (successful or otherwise) will be determined or judged (e.g.. what kind of evidence is needed and what kind of consensus is required).

3.2.2.2 Post-Decommissioning Conceptual Models

This section discusses pathways, driving forces, and processes that may result from interactions between the natural system, the creation of underground openings, the waste, and the sealing of the WIPP facility. These topics are discussed in greater detail in Sections 5 and 6. Independent system PA calculations are being performed using the Golder Associates' RIP PA model and will be documented separately as part of this PART effort, as discussed in Subsection 1.4.5. This subsection only discusses the primary natural barrier (i.e., the Salado), since the important interactions between the wastes and engineered barriers/components are all expected to be with Salado Formation rocks.

Figure 3-27 illustrates a modified version of an initial pathways flow chart that separates the 40 CFR 191 and 40 CFR 268.6 pathways. The plain boxes represent the possible component models, the labeled arrows indicate the possible paths (coupling) between the components, and the label along the path indicates both the fluid that would be transporting the waste or interacting with the next component and the driving force or important governing process. There are several pathways for transport of waste from the shadowed box in the center to the two compliance boundaries the shadowed boxes at the top.

The only additional pathway to the compliance boundary identified in Figure 3-27, beyond what is considered in the current PA, includes an additional type of borehole intrusion. This pathway considers a depressurization of the Bell Canyon as a result of oil and gas production outside the land withdrawal boundary (see the dense drill grid pattern east of the site, **Figure 3-28**), that could result in contaminated fluids moving from a disposal room to the Bell Canyon through an exploratory borehole (inadvertent human intrusion). The fluids may then migrate to the accessible environment (40 CFR 191 compliance boundary), with the potential exposure pathway being associated with oil/gas production outside the land withdrawal boundary. The PART also discussed the possible impacts of potash mining, but other than enhancements of the current pathways in the Rustler, no clear new pathway could be envisioned. The likely sequence of events includes slumpage of the surface that would lead to the formation of a catchment for summer high intensity storms, as well as a fracturing of the slumped harder rocks of the Rustler (e.g., Magenta and Culebra). The net effect would be localized enhancement of both the permeability of the Culebra and fresh water recharge. The enhanced recharge would in turn lead to enhanced dissolution of the soluble Rustler rocks.

SNL has not yet implemented a potash mining scenario, although it is one of the events that survived the scenario screening. The natural resource issue was one of EEG's concerns, presented in their discussions with the PART. As illustrated in **Figure 3-29** and discussed in Guzowski (1990), there are no potash resources over most of the waste panel area, but there are economical reserves to the north and northeast. However, EEG indicated that much of the area around the land withdrawal boundary is either leased, in litigation, or soon to be leased, and that potential impacts should be evaluated. An additional concern raised by EEG was related to the drilling frequency used in the PA calculations. By their calculations, the drilling rate has been 340 borehole/km^2/10,000 years (63 oil and gas wells in a 2 mile strip from 1977 to 1992), while the EPA maximum rate for intermittent drilling is 30. While the guidance to the regulations is very clear on the 30 borehole/km^2/10,000 years, and it is obvious that the EEG rate is a systematic exploitation rate and not a long-term intermittent exploration rate, as discussed in the guidance, there may be a need to address this issue. Because of the resource potential in the vicinity of

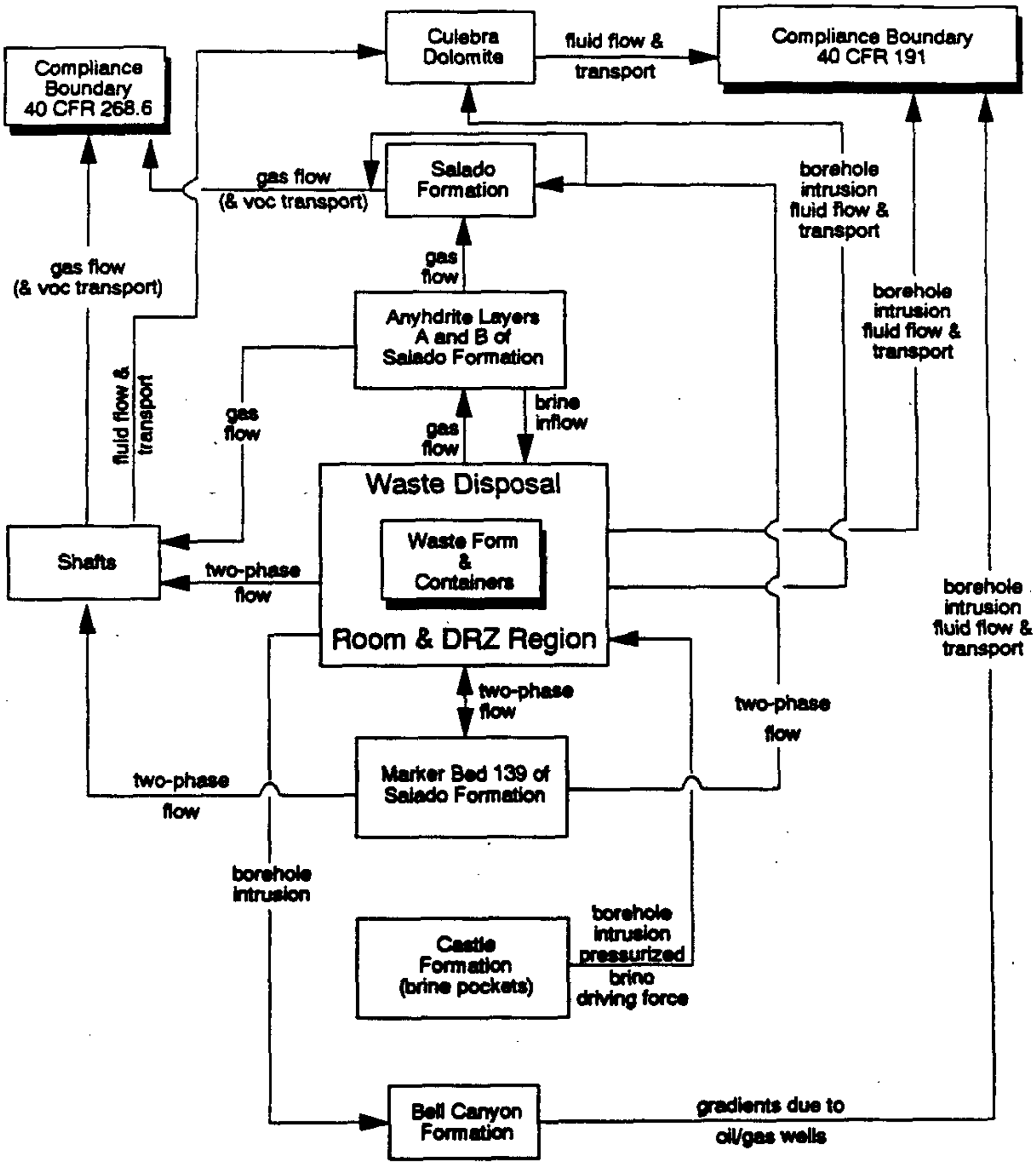


Figure 3-27. Potential Pathways and Models for the Post-Commissioning Time Period.

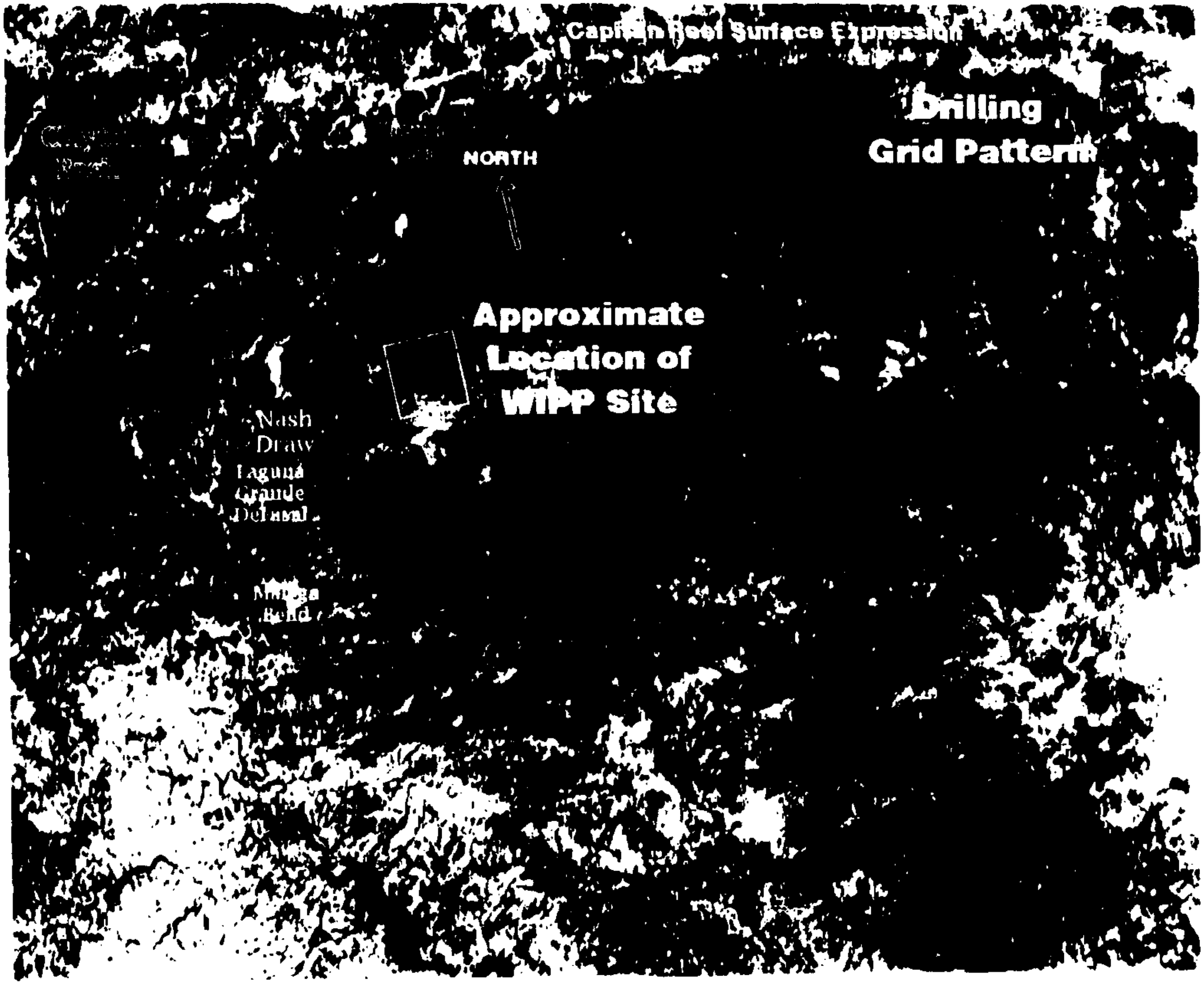


Figure 3-28. LANDSAT-1 Satellite Image of Southeast New Mexico (October 18, 1974) Showing the Approximate Location of the WIPP S[illegible] Relative to the Dense Drilling Grid Pattern East of the Site.

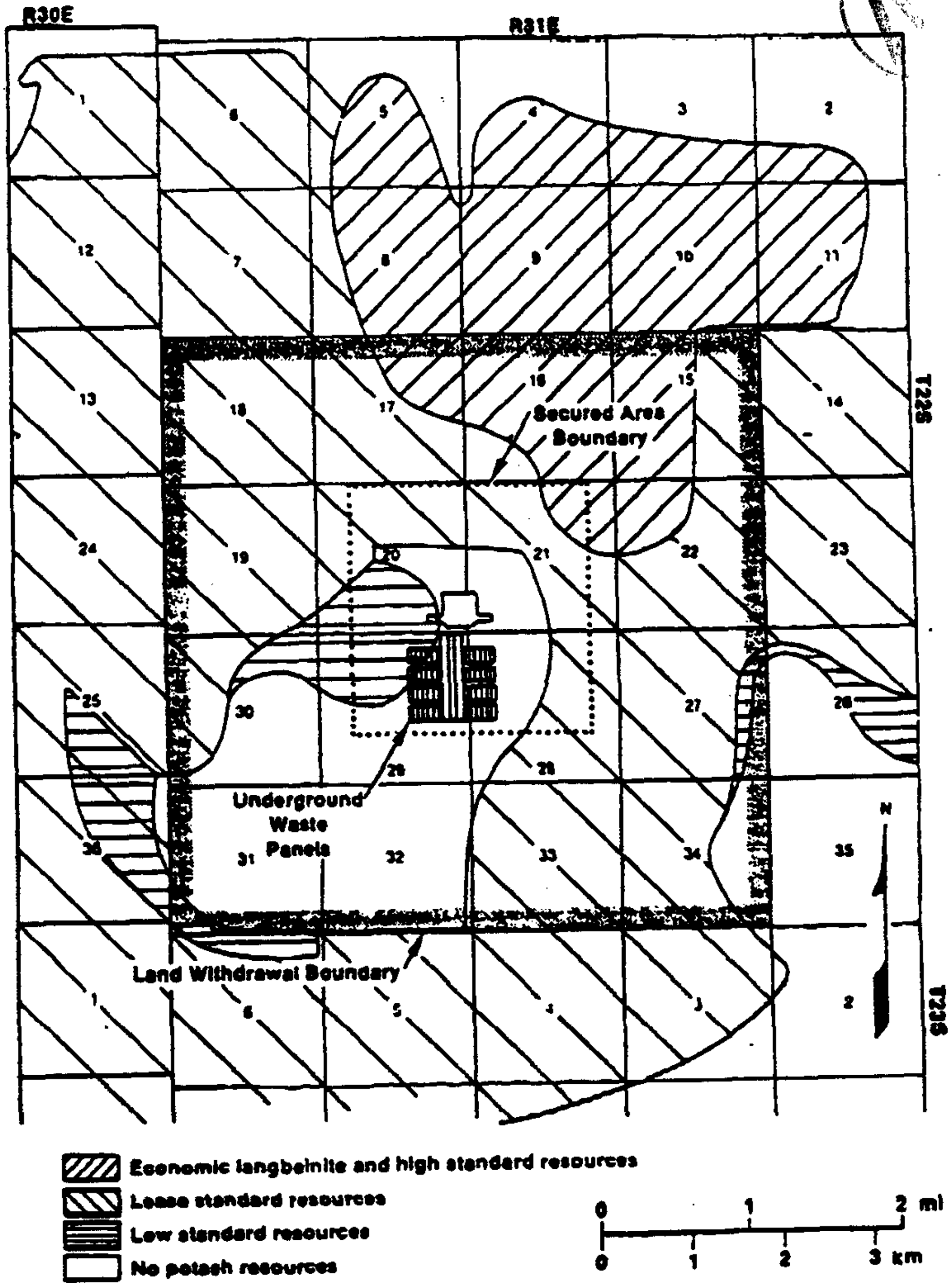


Figure 3-29. Generalized Distribution of Potash Resources in the Vicinity of the WIPP (reproduced from Guzowski, 1990; potash distribution from Brausch and others, 1982; base map from DOE, 1986).

the WIPP, the PART believes that the natural resource issue as raised in §191.14 (e), must be openly examined, in order to determine and clearly state DOE's position regarding the oil/gas and potash resources around the WIPP and address the EEG concerns regarding potash mining and drilling frequencies. The regulations do not preclude siting disposal systems in areas with natural resources, but they do require that the pros and cons be evaluated and clearly stated.

An additional geometric scale concern relates to dissolution and collapse features at the regional scale, see **Figure 3-30.** These sinks may be naturally occurring or may result from water injected in petroleum recovery processes, as noted by Baumgardner et al. 1982, p. 33: "Although the Wink Sink may be the result of natural processes, oil field operations in the area may be related to its formation." Given the proximity of petroleum operations to the WIPP site, care should be taken to monitor the salinity of injected and produced water and to monitor the ratio of water in to water out. This failure scenario may belong to a class of scenarios that have been addressed in the past and dismissed as not being of concern to the WIPP. Unfortunately, these previously considered and dismissed scenarios are not covered in the Annual PA Reports and are not currently available in a summary document. Such a summary document of the history of WIPP is being developed but will not be completed in time for the current review (Wendell Weart, May 27, 1993, personal communication).

Although large scale subsidence at the WIPP site appears unlikely, barring solution phenomena discussed above and given the relatively low extraction ratio, PA personnel, researchers, and designers should be aware that substantial subsidence has occurred over mine workings in the Carlsbad mining district. Miller et al. (1958), report on underground movement and subsidence over United States Potash Company Mine, which is located 22 miles east of the city of Carlsbad. These and other presumably abandoned mine workings may perturb the assumed hydrogeologic field in the repository region.

Beyond the issues related to inadvertent human intrusion, the major technical issues are associated with performing experiments and modeling to develop a credible characterization and understanding of the rocks and fluids of the Salado and the interactions of these rocks and fluids with the wastes and the engineered barriers and their various components, so that the required compliance analyses can be developed for the post-decommissioning phase. The first step involves understanding and characterizing the rocks of the Salado prior to the post-decommissioning phase, as this knowledge is needed to provide the initial conditions for the PA modeling of the post-decommissioning phase.

The technical issues prior to the post-decommissioning phase are associated with understanding and characterizing

- the initial development of the disturbed rock zone (DRZ), around each disposal room (**Figure 3-31**), the access drifts, and the shafts during construction (e.g., size and extent, and the effect on undisturbed rock properties);
- the subsequent evolution (during the various phases of repository development until post-decommissioning) of the DRZ surrounding the rooms and access drifts as a result of:
  a) the plastic flow of the salt due to high stress gradients,
  b) any excessive forces or high strain rates that could result in fractures developing as hypothetically shown in Figure 3-31, and
  c) the drying of the DRZ and surrounding rock mass as a result of drainage of the intergranular brines from the salt and nearby interbeds due to the altered properties of the

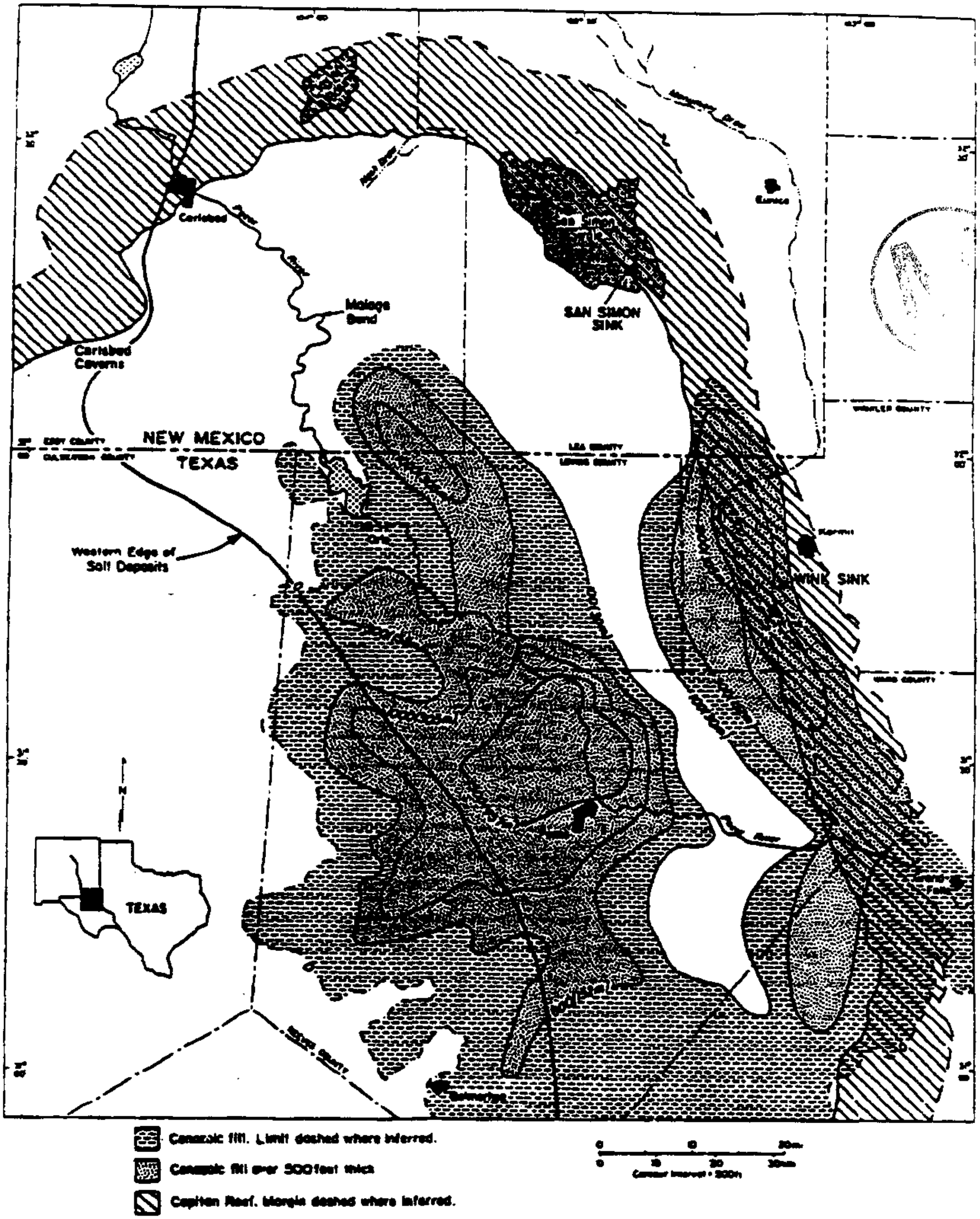
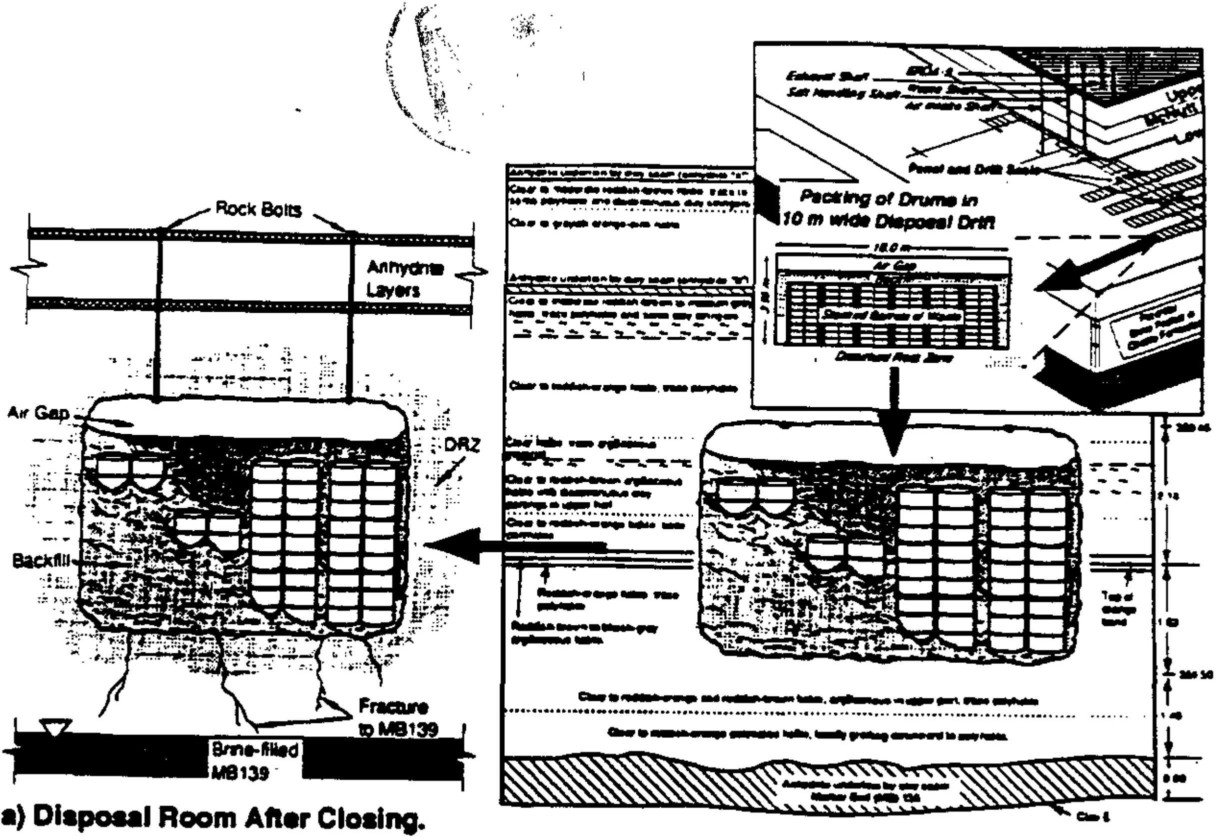
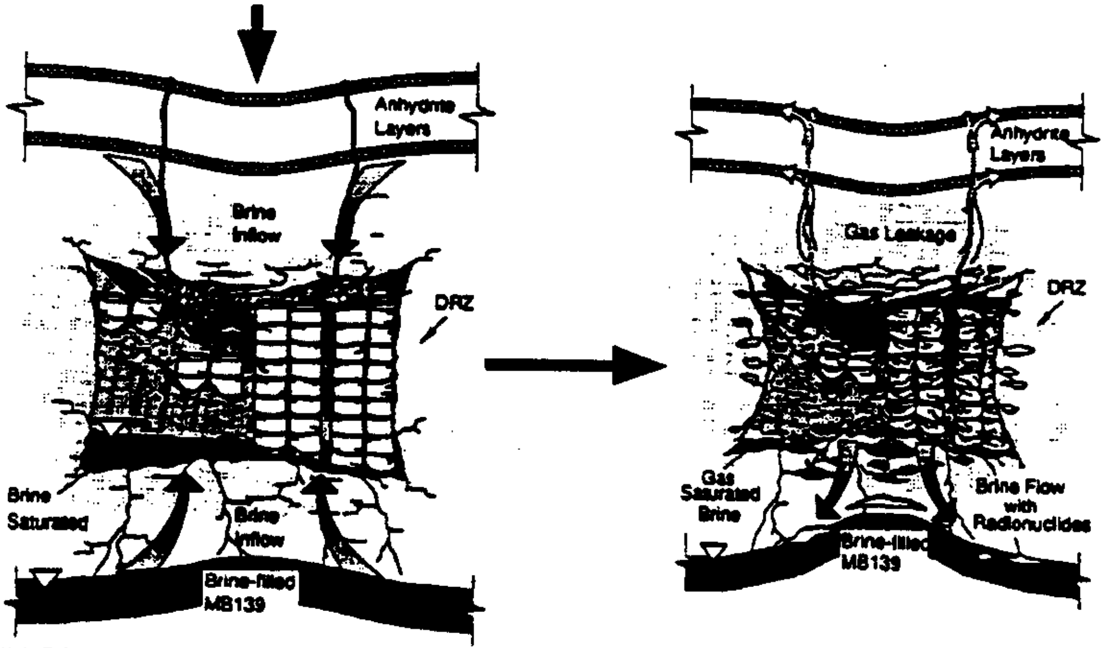


Figure 3-30. Dissolution and Collapse Features, and Isopach Map of Cenozoic Sediments, Delaware Basin. Cenozoic sediments more than 152 m (500 ft) thick (stippled area) overlie salt dissolution zones in center of basin and along eastern side. Other dissolution features coincide with subsurface trend of Capitan Reef on northeast side of basin. Adapted from Maley and Huffington (1953), Nicholson and Clebsch (1961), Hiss (1975), and Bachman (1976).



(a) Disposal Room After Closing.



(b) Disposal Room After Room Creep Closure and Brine Inflow.

(c) Disposal Room After Possible Gas Leakage, Room Expansion and Brine Inflow.

Figure 3-31. **Diagram Illustrating the Conceptual Evolution of a Disposal Room Within a WIPP Waste Panel. Illustrated in the upper left is the setting for a typical disposal room relative to the stratigraphy at depth and the progression of states, starting with (a) an idealized depiction of the disposal room after closure; (b) the disposal room after creep closure and brine inflow, and (c) the disposal room after possible gas leakage, room expansion and brine inflow. (Reference 1991 PA)**

DRZ, coupled with the tremendous gradients toward the openings and the enormous drying potential of the mine ventilation system;

- interactions with and effects on the closest interbeds above the drifts (anhydrite B, which is penetrated by rock bolts and underlain by clay seams, Figure 3-31) as well as the very heterogeneous marker bed 139 below the drifts, **(Figure 3-32).**

As illustrated in Figures 3-30 and 3-31, even the "thick halite" sections at the room emplacement horizon are rarely pure halite, but rather consist of various mixtures of halite, polyhalite, and argillaceous materials, as well as clay discontinuities.

The technical issues that must be investigated by compliance-based experimentation, characterization, and observations during the test phase and confirmed during the subsequent disposal phase are outlined in the following paragraphs. Some of the uncertainty in the following issues can possibly be addressed by avoidance through design changes (e.g., engineering aimed at preventing excessive pressure buildup in the disposal rooms) and by DOE planning (e.g., reducing the uncertainty in gas-generation rates and volumes through waste form requirements for that large fraction of the TRU wastes that has not yet been generated).

An understanding must be developed regarding how the DRZ and any associated fractures or other disturbances heal during creep closure of the drifts and shafts as the rock mass in the surrounding units of the Salado equilibrate with the emplaced wastes and room backfill, drift backfill, and seals, shaft seals, and any other emplaced engineered components (e.g., rock bolts). Two basically different conditions must be examined.

1) **Closure Under Conditions of Little Gas Generation.** Understanding is required for those conditions expected to occur (a) around shaft seals where there would only be interactions of the DRZ with the highly layered and heterogeneous Salado rocks along the vertical shafts (Figure 3-32) and the rather uniform and preconsolidated crushed salt backfill being considered for the shaft seals, and (b) in the partially backfilled access drifts and rooms of the operations region and experimental area (Figure 2.8).

   In these areas, and under these conditions, there would be few additional driving forces opposing room or shaft closure and DRZ healing as the entire system returns to pre-emplacement equilibrium. There is likely to be a small component of gas generation related to corrosion of the rock bolts and some resistance encountered as a result of compression of residual atmospheric gases in the void space above the crushed salt backfill in the drifts of the operational and experimental regions. These gases will compress and slowly dissipate into the surrounding accessible pore space, and some will dissolve in the intergranular brines that should move into the region during closure and healing.

2) **Closure Under the Conditions of Gas Generation.** Understanding is also required for those conditions expected to occur in disposal rooms where interactions among the waste, engineered components, and the Salado rocks and fluids (i.e., intergranular brines) will generate gases as a result of a variety of processes (e.g., anoxic corrosion of metals such as Fe and Al in the proposed containers, the waste, and engineering components like the rock bolts; microbial degradation of organic wastes such as cellulosics and rubber; radiolysis of brine and other waste components such as plastics; and volatilization of radioactive and hazardous VOCs).

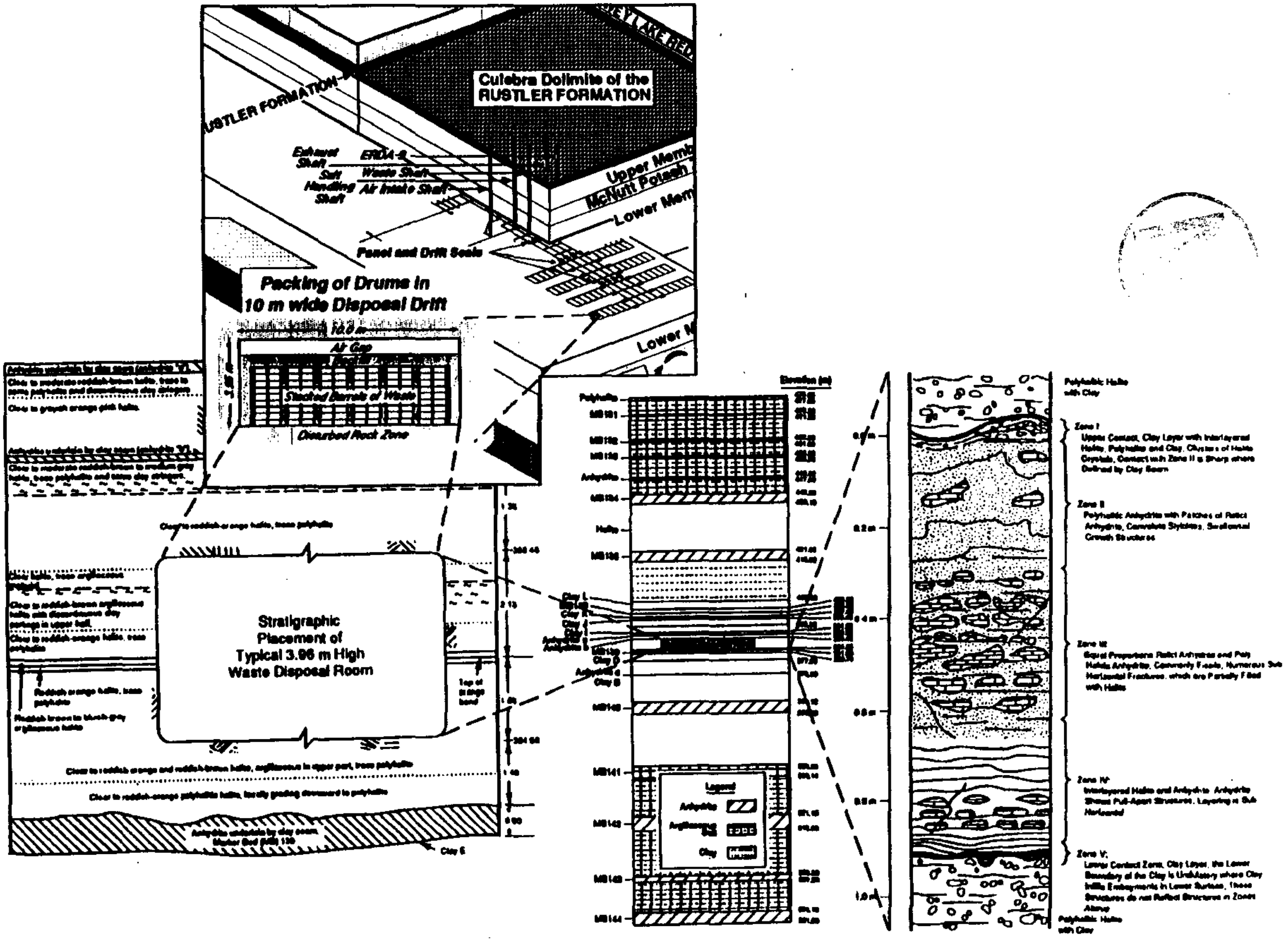


Figure 3-32. Illustration of the Various Scales of Spatial and Lithological Variation within the Salado Formation Near a Disposal Room and the Disposal Horizon.

Under these conditions, the behavior is much more difficult to understand fully and thus to predict with certainty because of the complicated coupling and interactions among the various processes involved. For ease of discussion, let "disposal room pore space" be defined as the combined pore space in (a) the wastes in various states of compression and degradation, (b) any remaining headspace in the disposal room drift (i.e., the air gap illustrated in Figure 3-31), (c) the backfill located in the disposal room drifts around the waste, and (d) the DRZ and any fractures associated with these drifts. While the processes and interactions are complex, it is believed that if gas is produced in the appropriate volumes, transport toward the accessible environment can occur (most likely through the anhydrite layer B or MB-139, Figure 3-31) as illustrated in the pathways diagram, Figure 3-27. The increased pressure associated with gas generation provides the driving force, and the generated gases provide the vehicle for transport of any hazardous and radioactive wastes that might volatilize into the disposal room pore space. The various processes expected to be active and their principal effects are outlined below, borrowing five items from the discussions in DOE/WPIO/001-92, 1992; Chan et al., 1992; Davies et al., 1991; and Davies, 1991.

- *Gas generation processes* increase the volume of gas in the disposal room pore space. It is also important to note that both the rate of generation and the total volume of gas generated are dependent on the rate of brine inflow. Gas generation rate therefore can be modulated (i.e., increased or decreased) in response to changes in the brine inflow rate to the disposal room pore space.
- *Mechanical processes* of room closure and consolidation of the materials within result in a reduction of the disposal room pore space and changes in other physical properties of the materials being consolidated (e.g., lowering of the permeability). This process is driven by lithostatic forces that can be opposed by the backstress on the salt provided by fluid pressure buildup in the disposal room pore space.
- *Multiphase fluid flow and transport processes* control the flow of fluids (i.e., gases and brine) into and out of the disposal room pore space and the pore space of the surrounding Salado rocks. Flow is driven by the differences in pressure between the fluids of the surrounding Salado rocks and the fluids in the disposal room pore space in a nonlinear way that is highly dependent on the state of connectivity of the wetting (i.e., brine) and non-wetting (i.e., gases) fluid phases . According to Davies (1991), large threshold pressures may be required to initiate gas penetration and movement in the brine-saturated matrix of Salado rocks that is highly dependent on the type and purity of the Salado evaporites; see Subsection 5.4 for a discussion of threshold pressures.
- *Pore space dilatation* can result if excessive pressures build up in the disposal room pore space, and a phase of disposal room expansion can result. These excessive pressures can give rise to pressure-sensitive inelastic flow that can result in interface separation in the bedded salts of the Salado, fracture extension/expansion, and other forms of damage evolution in crystalline evaporite solids of the Salado.
- *Dissolution and exsolution of gases* occur when gases in the disposal room pore space and gases migrating in the interbeds come into and remain in equilibrium with the gases dissolved in the brines that can coexist in the pore space by moving into and out of solution, depending on the pressure/solubility relationship.

As discussed in Davies et al. (1991), the above processes are highly coupled. The actual pressure history in the disposal room pore space is dependent on the volume of disposal room pore space (mechanical processes of room closure and consolidation; pore space dilatation) and the difference between the rate of gas generation and the rate that fluids can leave the disposal room pore space (multiphase fluid flow and transport processes).

One possible sequence of states is illustrated in Figure 3-31 (a-c) and details will be discussed in Sections 6 and 7.

The potential for the waste to generate gas requires that any potentially negative responses to gas generation be evaluated. For example, if sufficient quantities of gas are generated and released to the nonhalite interbeds, there is a possibility for this generated gas to (a) disrupt the drift and panel sealing process (depending on how soon the release occurs), and/or (b) transport hazardous gaseous wastes (e.g., VOCs) to the compliance boundary (DOE/WPIO/001-92, 1992). If the disposal rooms or panels seal sufficiently to form pockets of highly pressured brine and gases, these localized pockets could potentially increase or decrease the effects associated with human intrusion. These effects, and the various possible methods for dealing with the uncertainties associated with room closure, under conditions of gas generation, need to be evaluated. Some of the general sources of uncertainty include lack of an appropriate level of knowledge regarding

- the actual character of the waste;
- the potential amount and type of gases that can form;
- the rate of gas generation;
- the potential closure sequences and end closure states; and
- the processes needed to predict the potential closure and consolidation sequences and the end closure states.

4.0 WIPP SITE NATURAL SYSTEM

Critical to any PA is the geology of the site where the waste will be emplaced. In this section, the undisturbed natural hydrologic and other properties of the geologic formations at the WIPP site are described in order to provide a starting condition from which to evaluate subsequent perturbations. The formations described in this section are the Castile (Subsection 4.1), which begins about 200 m (650 ft) beneath the repository level; the Salado (Subsection 4.2), which is the host formation; the Rustler (Subsection 4.3), which is considered to contain the most likely pathway for transport of radionuclides to the accessible environment, and the Dewey Lake Redbeds which, although they may not represent a pathway for the migration of radionuclides, may control the flow of recharge to the underlying units of the Rustler Formation.

According to Mercer (1983), the majority of geologic studies in the area prior to the beginning of the WIPP project in 1972 were confined to the Bell Canyon Formation and units below it, although extensive work has been done by the potash industry in the overlying strata. These units below the Salada Formation have been heavily studied for more than fifty years because of their oil/gas resource potential. The first discussions of the geologic units above the Bell Canyon were by Lang in 1937. This geologic study was followed closely by the first hydrologic study of the area (Robinson and Lang, 1938), which, in turn, initiated a series of studies continued until at least 1980, on the Malaga Bend salinity problem. The other significant geologic and hydrologic studies conducted in the area (particularly the Rustler) were undertaken as part of the Gnome experiment (Figure 3-15) which involved an underground nuclear test in salt.

Early WIPP investigations began with a review of the geology and hydrology of the Carlsbad potash area by Brokaw et al. (1972), according to Mercer (1983). Other early WIPP efforts included studies by Jones et al. (1973) and by Mercer and Orr (1977) on the Los Medanos area and the regional hydrology of the WIPP area, respectively and by Powers et al. (1978). Also, as discussed in Mercer (1983), hydrologic study details are presented in data reports by Mercer and Orr (1979) and Mercer and Gonzalez (1981).

According to Lappin et al. (1989), the data on the Rustler Formation presented in DOE's 1980 FEIS were derived from testing performed at eight locations, while Mercer indicates that his 1983 study, data collection and interpretations were based on efforts undertaken and hydrologic data collected from tests conducted over seven years, starting in 1975, at thirty-nine wells which were drilled for or converted to hydrologic test holes. Mercer's 1983 efforts provided estimates for determining potential hydrologic boundaries (Figure 3-15), potentiometric head distributions (e.g., Figure 3-13), groundwater chemistry, hydrologic properties from pumping, slug, pressure-pulse, and tracer tests, and the location of dissolution fronts based on halite distribution. The discussions on the Rustler presented by Lappin et al. (1989) were based on information collected from a total of forty-one well locations.

From the limited number of documents reviewed by the PART, it appears that Mercer's hydrologic investigation and interpretation form the basis for much of the regional interpretation of the supra-Salado hydrologic system at WIPP. The 1992 PA discusses a preliminary geohydrologic conceptual model developed by Brinster (1991), but this report was not reviewed by PART.

Dissolution in the WIPP area is complex and is considered in a series of articles on the Cenozoic history of the area starting with Bachman in 1973 (Mercer, 1983). Mercer further indicates that additional interpretations of dissolution have been prepared by Anderson, 1978 and 1981, and Lambert, 1982. The whole series of issues and controversies regarding the origin of the regional dissolution in the Rustler Formation is summarized in LaVenue et al. (1990). Some of the authors and studies reviewed by PART include Bachman (1980 and 1985); Snyder (1985); Chaturvedi and Channell (1985); Lowenstein (1987); and Holt and Powers (1988).

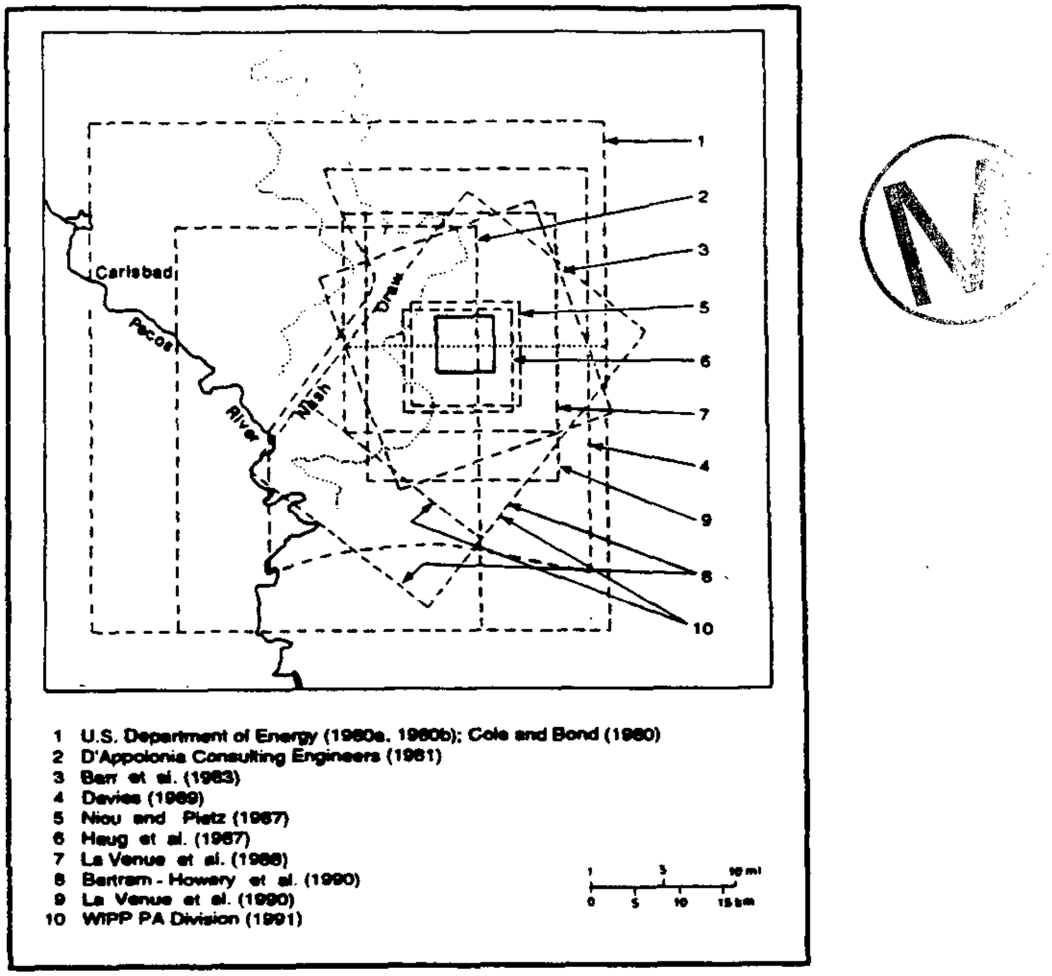
The eleven groundwater modeling studies of the Rustler and/or the Culebra through the 1991 modeling by the WIPP PA division are illustrated and summarized in **Figure 4-1**, taken from LaVenue and RamaRao (1992). The LaVenue and RamaRao modeling study discusses the use of a completely automated inverse procedure to develop seventy calibrated conditional simulations for the Culebra transmissivity field based on the use of steady-state and transient field pressure data. These seventy realizations were the basis for the 1992 PA calculations. Lappin et al. (1989), as well as Davies (1989) and LaVenue et al. (1989), summarize many of these studies through 1990. Davies' study represents the only variable density modeling (a 2D subhorizontal section model). Current PA models assume the Culebra to be a totally confined, vertically homogeneous, and laterally isotropic unit with no vertical flux, even though the Davies (1989) and Haug et al. (1987) studies support the vertical flux concept, (Lappin et al., 1989).

SAND88-0196 edited by Siegel et al. (1991) is a compendium of six hydrochemical studies of the Rustler. Their brief interpretation of these studies is that modern flow within the Culebra is largely north to south; however, as already discussed in Subsection 3.2.2, this flow direction (assumed equilibrium) is inconsistent with the salinity distributions in the region. Siegel et al. (1991) also postulate that eastward increasing $^{234}\mathrm{U}/^{238}\mathrm{U}$ activity ratios could imply a Pleistocene infiltration zone flowing from the west-northwest and thus imply a change in flow direction during the last 30,000 to 12,000 years.

4.1 CASTILE FORMATION

The Castile Formation, beginning about 200 m beneath the repository level, consists of about 470 m of interbedded anhydrite and halite resting on the Bell Canyon Formation. The uppermost anhydrite layer of the Castile contains isolated pockets of pressurized brines that occur in limited reservoirs characterized by fracture porosity in a very tight matrix (Popielak et al., 1983; Lappin et al., 1989). These brine pockets have been encountered in thirteen of about 100 wells that have penetrated the Castile Formation, including the WIPP-12 reservoir 1.6 km (1 mile) north of the center of WIPP (Lappin et al., 1989, Figure 3-26). Time domain electromagnetic methods (TDEM; Ertech, 1988) measurements detected the brine occurrence at WIPP-12 and indicate that brines may be present within the Castile Formation under a portion of the WIPP waste panels (Lappin, 1988).

Popielak et al. (1983), in a characterization of Castile brine occurrences and detailed discussion of ERDA-6 and WIPP-12 testing, found the reservoirs to be chemically distinct from each other and from local groundwaters. The ERDA-6 and WIPP-12 halite-saturated brine reservoirs, with estimated volumes of 1.0×10^5 and 2.7×10^6 m^3, respectively, are located in fractured anhydrites above thickened halite. About 5% of the brine volume is stored in large open fractures; the remainder occurs in low-permeability microfractures. Median parameter values (PA 1992, 3, pp. 4-10) for permeabilities of the intact and fractured anhydrite matrix are 1×10^{-19} m^2 and 1×10^{-13} m^2, respectively, an intact porosity of 5×10^{-3}, fluid pressure of 12.7 MPa (lithostatic and hydrostatic pressures are about 20 and 9 MPa, respectively), and bulk storativity of about 0.2 m^3/Pa (volume of fluid discharged/unit decrease in reservoir pressure).



Reference	Hydrogeologic Unit Modeled	Head Calibration
U.S. DOE (1980a,b)	Rustler	Steady State
D'Appolonia (1981)	Rustler	Steady State
Cole and Bond (1980)	Rustler	Steady State
Barr et al. (1983)	Culebra	Steady State
Davies (1989)	Culebra	Steady State
Niou and Pietz (1987)	Culebra	Transient
Haug et al. (1987)	Culebra	Steady State
LaVenue et al. (1988)	Culebra	Steady State
Bertram-Howery et al. (1990)	Culebra	Steady State
LaVenue et al. (1990)	Culebra	Steady State/Transient
WIPP PA Division (1991)	Culebra	Steady State

Figure 4-1. **Summary of Early Rustler and/or Culebra Modeling Studies: (a) Approximate Boundaries of Groundwater Flow and Transport Models in the WIPP Region (reproduced from Lappin et al., 1989, from Davies, 1989); (b) Summary of these Investigations (reproduced from LaVenue and RamaRao, 1992).**

These brine pockets are of limited extent, have been isolated for long periods of time, and pose no threat to the overlying repository in the undisturbed state.

4.2 SALADO FORMATION

Bedded salts (**Figure 4-2**) in general contain appreciably more water (0.1 to 1.0 wt %) than do domal salts (less than .01 wt %), not only because of interbedded clays and other hydrous impurities within the halite layers, but also because of fluid inclusions (**Figure 4-3**) trapped by rapidly accreting halite crystal faces. Knauth and Beeunas (1986) studied oxygen (^{18}O) and deuterium isotope concentrations in brines from fluid inclusions in halite crystals from Salado salt and found that the brine has a composition consistent with that of connate waters trapped during evaporation of Permian seas. Intracrystalline brine inclusions in the Salado, however, do not constitute a viable source for brine because high temperatures and substantial thermal gradients are required for their migration to boundaries of halite crystals. Intergranular water, that between grains forming the rock salt layers, may be available for transport and does exist in the Salado, as evidenced by weeps in the WIPP rooms (e.g. Deal and Case, 1987; Nowak et al., 1988; Tyler et al. 1988; Bredehoeft, 1988; Lappin et al., 1989). However, these mined surfaces and boreholes have been disturbed by the excavations, and at the very low permeability of undisturbed Salado salt (less than 10^{-21} m^2), even extremely slow flow of brine through the salt is both questionable and negligible.

Forty-five anhydrite- and polyhalite-rich interbeds or marker beds (MB) in the Salado Formation have been identified and numbered; other thinner, but laterally persistent, interbeds of clay, anhydrite, and polyhalite occur throughout the unit. Waste disposal panels are excavated between MB 138 and MB 139; floors of rooms are 1.4 m (4.55 ft) above MB 139 and roofs are 12 m (39 ft) below MB 138. These interbeds, especially MB 139, along with anhydrate layers A (5 m {16.25 ft} above the roofs) and B (2.6 m{8.45 ft}above roofs), are regarded as primary potential pathways for migration of brine and gas because of their higher intrinsic permeability compared to halite layers and their brittle behavior relative to the ductile or plastic and self-healing behavior of the halite. Borns (1985) described the petrologic character of the heterogeneous, 1 m-thick (3.3 ft) MB 139 (Figure 3-32). The top of the bed is defined by a clay layer with intercalated halite, polyhalite, and clay. This thin layer grades downward to a 0.6 m-thick (1.95 ft) layer first dominated by polyhalitic anhydrite containing patches of relict anhydrite, followed by a zone of equal proportions of the two rock types. This lower zone, about 0.3 m-thick (0.97 ft), is readily separated along subhorizontal planes (fissile) and contains subhorizontal fractures partially filled with halite. The base unit of MB 139 consists of 0.15 m-thick (0.49 ft) interlayered halite and anhydrite, grading into the lowermost contact zone, an undulating clay layer.

Halite's undisturbed permeabilities, estimated primarily from multipacker test-fluid pulse withdrawal results, range from too low to measure to 6.8 X 10^{-22} m^2. Anhydrite far-field values range from 3 X 10^{-20} to 4.4 x 10^{-20} m^2, generally one to two orders of magnitude higher than for the halite (Gorham et al., 1992, Table 3). Far-field pore pressure in the anhydrite is apparently well-established at near 12.5 MPa, whereas that in nearby halite is about 3 MPa lower; these values may be compared with hydrostatic and lithostatic pressures of about 7.0 and 14.8 MPa, respectively (1992 PA, Volume 3, p. 2-40). Porosity of both halite and anhydrite in the far-field, based on drying experiments, and electromagnetic and DC resistivity measurements, ranges from .001 to .03 with a median value of .01, in accord with grain and bulk density determinations (PA, 1992, Volume 3). The flow properties of the Salado Formation are very heterogeneous; each tested halite layer and interbed has its own characteristics

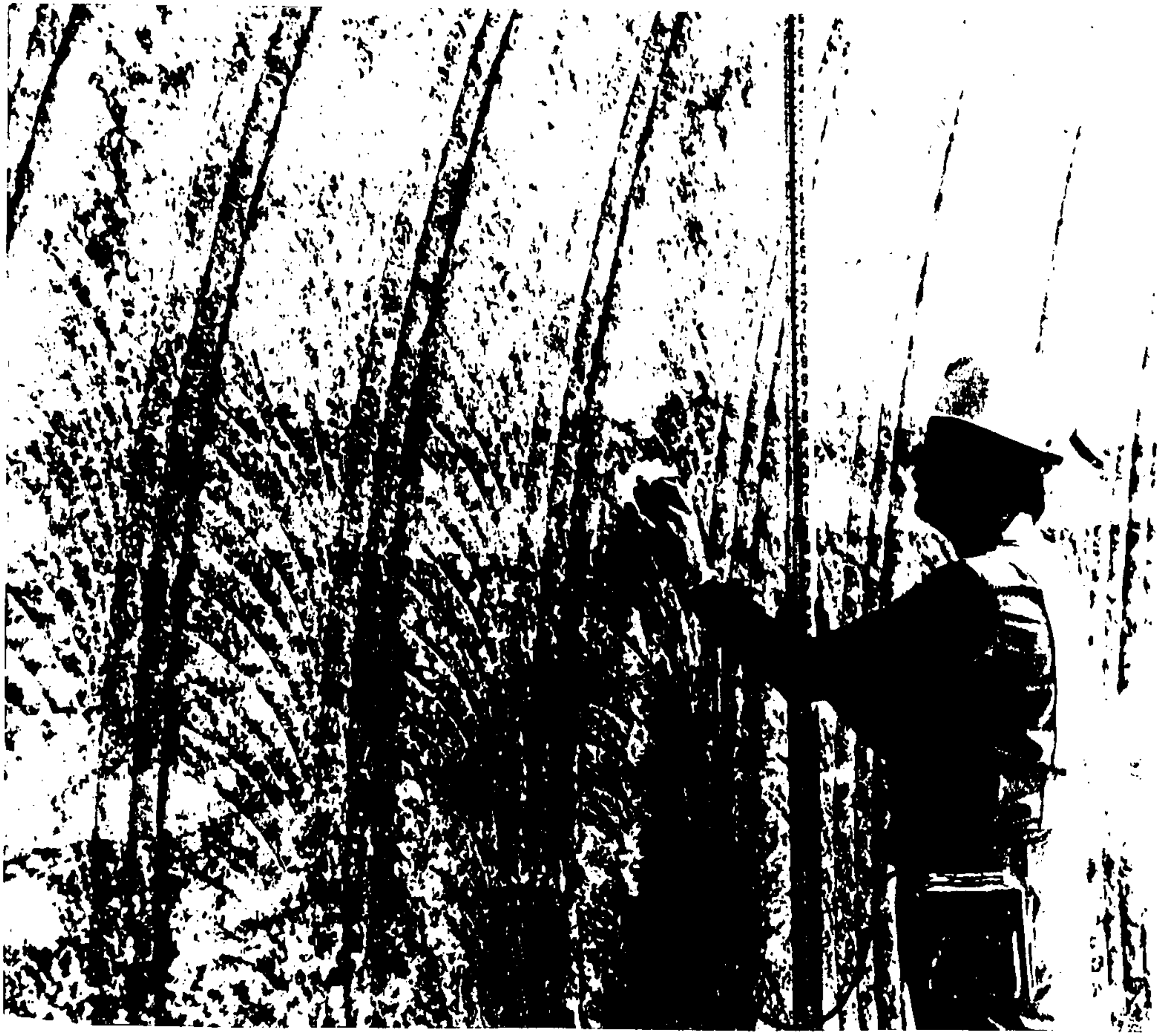


Figure 4-2. Photograph of the Salado Formation at the Repository Horizon. Dark vertical lines were created by the mining equipment. The pink horizontal bands are composed of relatively pure (light) and impure (dark) halite.

Figure 4-3. Fluid Inclusions in Halite Crystal.

(Howarth et al., 1991). As pointed out by Beauheim et al. (1991), information available is still insufficient to validate the assumption that brine migration through halite of the Salado Formation occurs by Darcy flow through a porous medium in response to continuous pore pressure gradients, rather than by flow initiated through connections of isolated pores following a disturbance (McTigue et al., 1989).

4.3 RUSTLER FORMATION

The Rustler Formation (**Figure 4-4**) is considered to contain the most likely pathway for transport of radionuclides to the accessible environment (SAND92-0700/2, 1992), since it lies directly above the Salado Formation and contains the most productive hydrostratigraphic units in the WIPP area (Mercer, 1983). Specifically, the Culebra Dolomite Member of the Rustler Formation has been identified in the scenarios developed for long-term performance assessment as the unit that could provide a path to the accessible environment in the event of inadvertent human intrusion for petroleum resources (DOE/WIPP 89-011, 1993). Subsection 4.0 discussed the general stratigraphy, geohydrologic setting, and geohydrology of the supra-Salado hydrologic system for the area around the WIPP site. This subsection presents more detailed information on the Rustler Formation, specifically the Culebra Member, and discusses ongoing and planned activities as they relate to the PA modeling of the Culebra.

4.3.1 Rustler Formation Stratigraphy, Hydrology, and Chemistry

According to Mercer, the Rustler Formation, which is a key marker of the Permian, was named by Richardson (1904), and the five-fold division of the Rustler (left side of Figure 4-4) was described by Vine (1963). Five transmissive Rustler units are now recognized, as illustrated in Figure 4-4 instead of the three (Culebra, Magenta, and the residuum at the Rustler-Salado contact) recognized at the time of the FEIS (Lappin et al., 1989). As illustrated in Figure 4-4 a water producing mudstone/halite unit has been identified within both the Forty-Niner and Tamarisk Members. The variation in the thickness of the Rustler Formation from 8.5 m (27 ft) west of the site through 95 m (309 ft) at WIPP to 216 m (712 ft) east of the site is attributed to thinning by dissolution and erosion (SAND92-0700/2, 1992). This is attested to by the three breccia and claystone zones (**Figure 4-5**) that abut their corresponding halite zones within the Rustler. These zones, interpreted by Chaturvedi and Channell (1985), are referred to as the upper, middle, and lower dissolution residues. However, the laterally-varying depositional facies model of Holt and Powers (1988) has considerable merit. As indicated in Snyder (1985), a complete unaltered thickness of all members of the Rustler can only be found east of the WIPP site. The lithology, thickness variation, and other hydrologic characteristics of the five members of the Rustler Formation are briefly summarized in the following subsections, starting at the top of the Salado Formation.

4.3.1.1 The Unnamed Lower Member

This member is 36 m (117 ft) thick at the WIPP site (SAND92-0700/2, 1992) and consists of laminated to massive dark-gray siltstones and fine grained sandstones overlain by alternating beds of halite, siltstone, and anhydrite (Snyder, 1985; Lowenstein, 1987). Increasing amounts of halite are present to the east (Figure 4-5), and a contact residuum (**Figure 4-6** c) that is quite variable in thickness (2.4 to 33 m {7.8 to 1.07 ft}) underlies the Rustler in the area of Nash Draw (Mercer, 1983; SAND92-0700/2, 1992). The basal unit of this member is the transmissive hydrologic unit, and its transmissivity increases to the west in Nash Draw due to fracturing of the basal siltstones and sandstones, possibly a

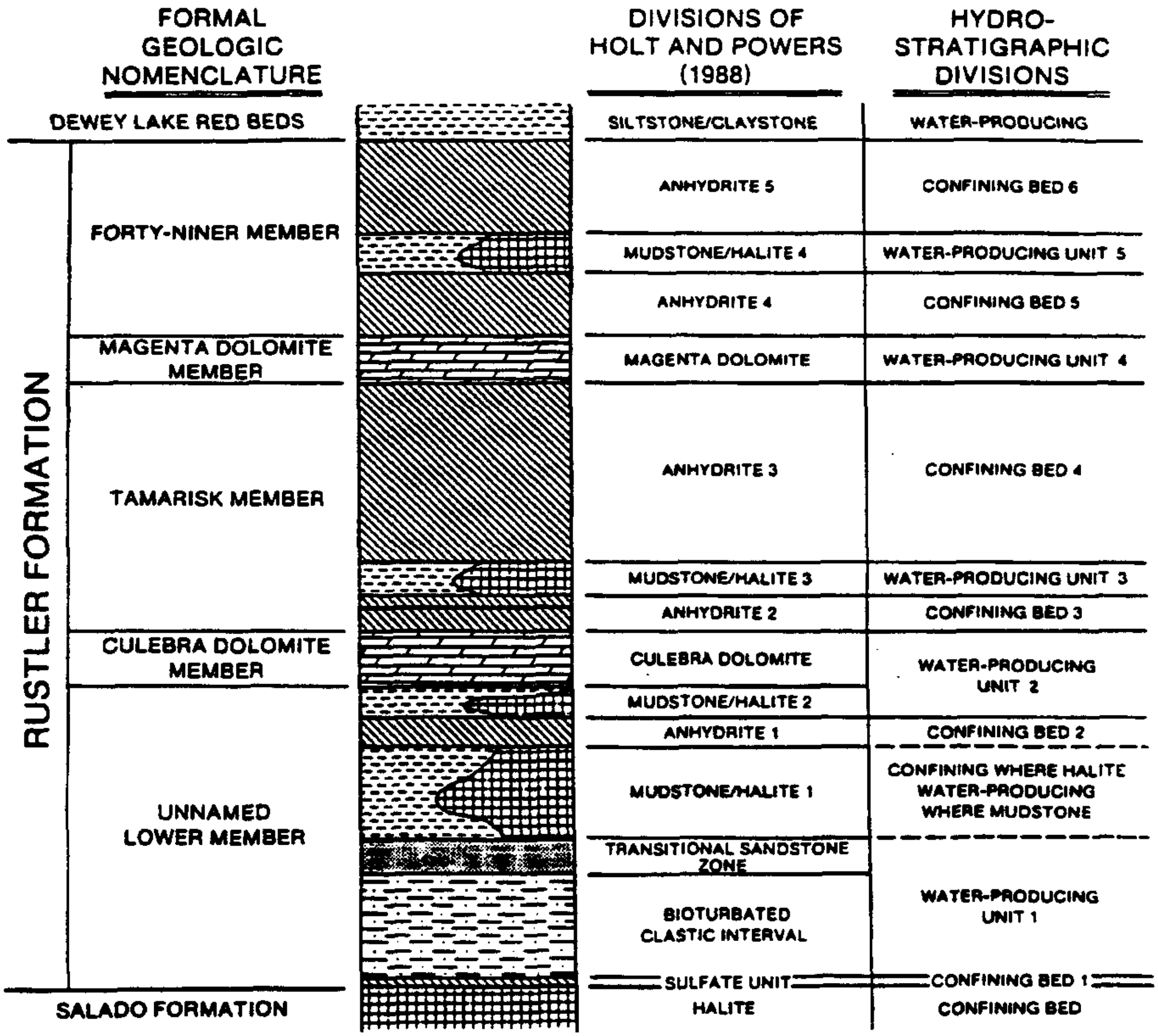


Figure 4-4 Hydrostratigraphic Column of the Rustler Near the WIPP Site (reproduced from SAND89-0462, 1989, but prepared by Beauheim and Holt, 1990).

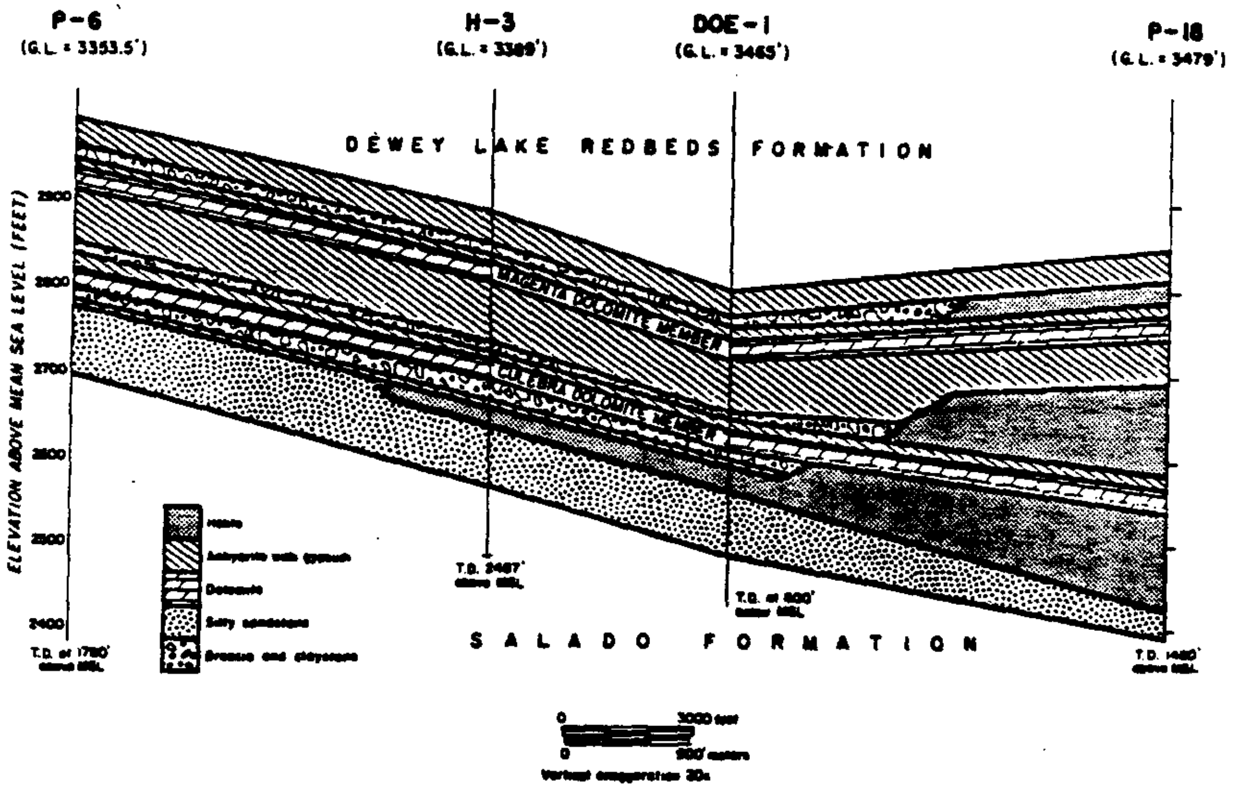


Figure 4-5 Geologic Cross Section of the Rustler Formation at the WIPP Site (reproduced from Chaturvedi and Channell,1985).

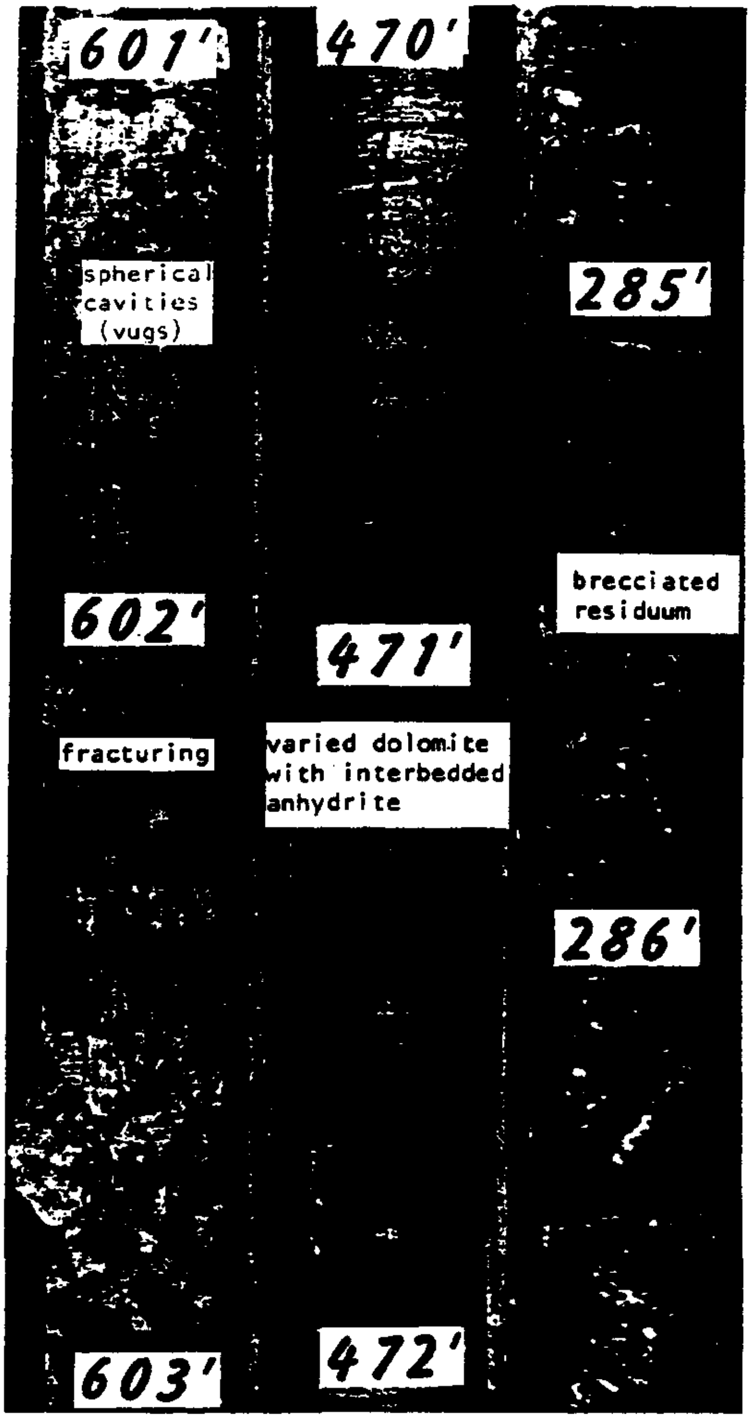


Figure 4-6. Core sections from Hydrologic Units of the Rustler and Salado Formations (reproduced from Mercer, 1983): (a) H-8C, Culebra Dolomite Member; (b) H-8A, Magenta Dolomite Member; (c) H-7C, Rustler-Salado Contact Residuum.

result of dissolutioning of the Upper Salado Formation and subsequent subsidence (SAND92-0700/2. 1992). The interpreted potentiometric surface for this hydrostratigraphic unit (Figure 3-22) was presented earlier (Subsection 3.2.2.1).

As discussed in chapter 1 of Siegel et al. (1991), most of the data from the non-Culebra units overlying the Salado are reported in Mercer (1983) and Beauheim (1987). Mercer (1983) indicates that waters in the Rustler-Salado contact zone or in the residuum contain the highest concentrations of TDS (79,800 mg/l at H-7 to 480,000 mg/l at H-1) in the WIPP area. Mercer assumes that large magnesium concentrations result from brines having had time for extensive interaction with their host rock and thus represent no or very slow circulation. He observed that these concentrations decrease one to two orders of magnitude in the area (**Figure 4-7**) and constructed an isoconcentration line (2000 milliequivalents per liter of potassium and magnesium combined, Figure 4-7) that approximates a dividing line between the zones of generally small concentrations to the west and the rapidly increasing concentrations to the east; [he also indicates that it represents a division of minute eastern transmissivity, 10^{-4} m^2/day (10^{-3} ft^2/day), to greater western transmissivity, 10^{-2} m^2/day (10^{-1} ft^2/day)]. Given his basic assumption and the lack of residuum east of this line, he concludes that it separates the active circulation zones to the west from the undeveloped flow system east of this line.

4.3.1.2 Culebra Dolomite Member

The Culebra Dolomite Member varies in thickness in the WIPP area from 4 to 11.6 m (13 to 37.7 ft) (mean 7 m {22.7 ft}; the PA Department uses 7.7 m {25 ft}) and is described as a vuggy microcrystalline dolomite or dolomitic limestone some of whose solution cavities (vugs) contain halite or gypsum (Figure 4-6 a), (Mercer, 1983; Snyder, 1985; SAND92-0700/2-3, 1992). This member is confined over most of the area by the mudstone/halite and anhydrite units of the unnamed lower member that it overlies and the thick anhydrite unit of the Tamarisk that overlies it (**Figure 4-8**), (Mercer, 1983). The structural character of the Culebra, according to Mercer (1983), is directly related to the character of dissolutioning of underlying units, and, as noted in SAND92-0700/2 (1992), "there is an apparent correlation between the absence of halite and increased transmissivity in the Culebra Dolomite Member." This is a result of subsidence and subsequent fracturing of the dolomite, as illustrated in **Figure 4-9**, which shows the highly fractured Culebra Dolomite resulting from halite removal at outcrop (Mercer, 1983). Discussion in the 1992 PA (SAND92-0700/2) indicates that the majority of the variability in hydraulic conductivity is believed to be controlled by open fractures (although no measurements of the density of open fractures is available due to poor recovery) because little variability was observed in the depositional environment and "primary features" of the unit. These discussions also indicate suspected correlations between open fracture density and the following features:

- overburden thickness,
- halite in surrounding members of the Rustler Formation,
- dissolution of halite, and
- the distribution of gypsum filling in fractures.

Other evidence of the variable nature of the Culebra structure is illustrated by the variable nature of the horizontal cores removed from Culebra units 3A and 3B (within 55 ft of each other horizontally and 5 ft vertically) in the air intake shaft at WIPP (**Figure 4-10**). These cores will be used in retardation experiments (to be conducted by Fred Gelbard, SNL, who was interviewed by the PART) that are

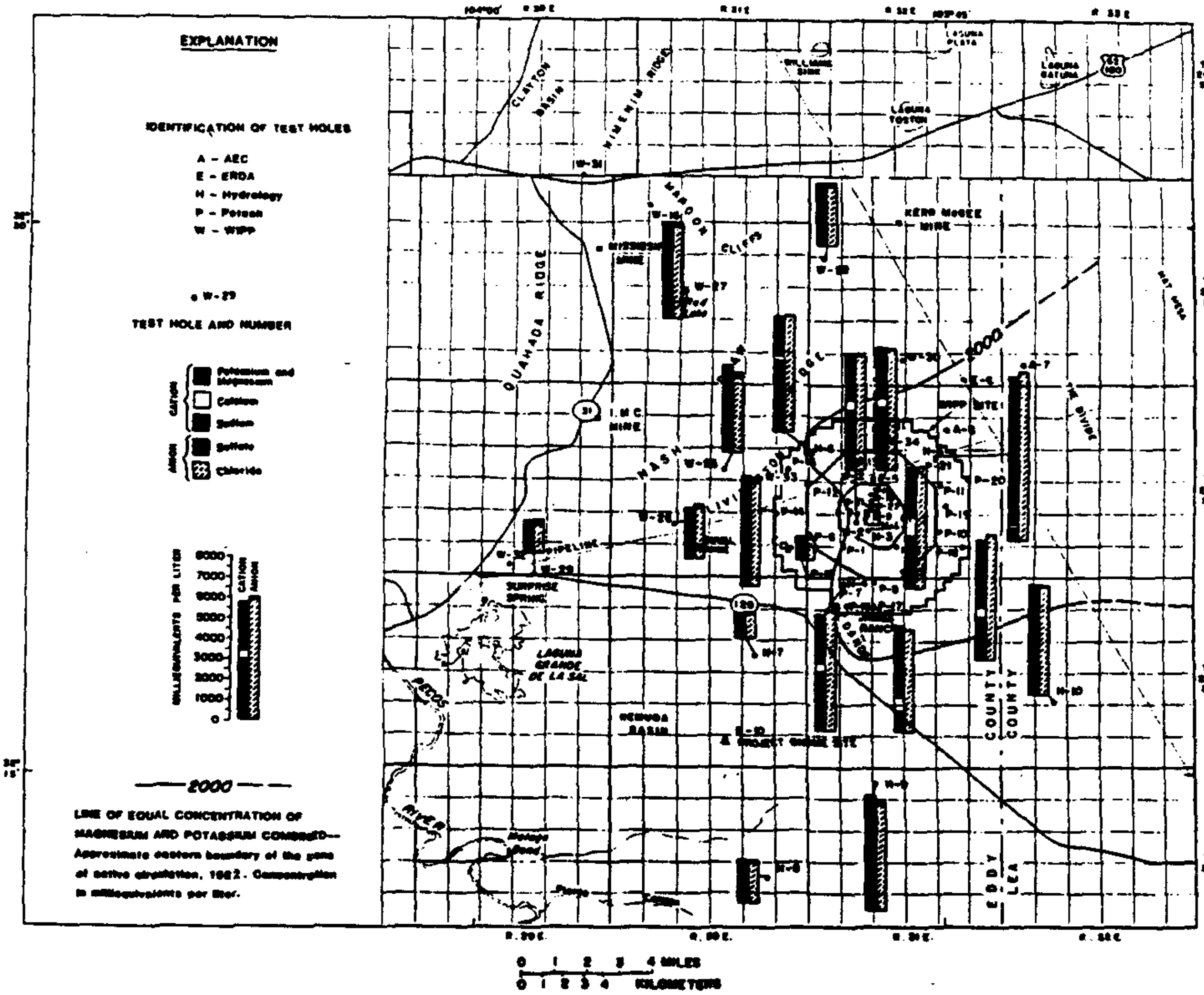


Figure 4-7. Concentrations of Major Chemical Constituents in Water from the Rustler-Salado Contact Residuum at and Near the WIPP Site (reproduced from Mercer, 1983).

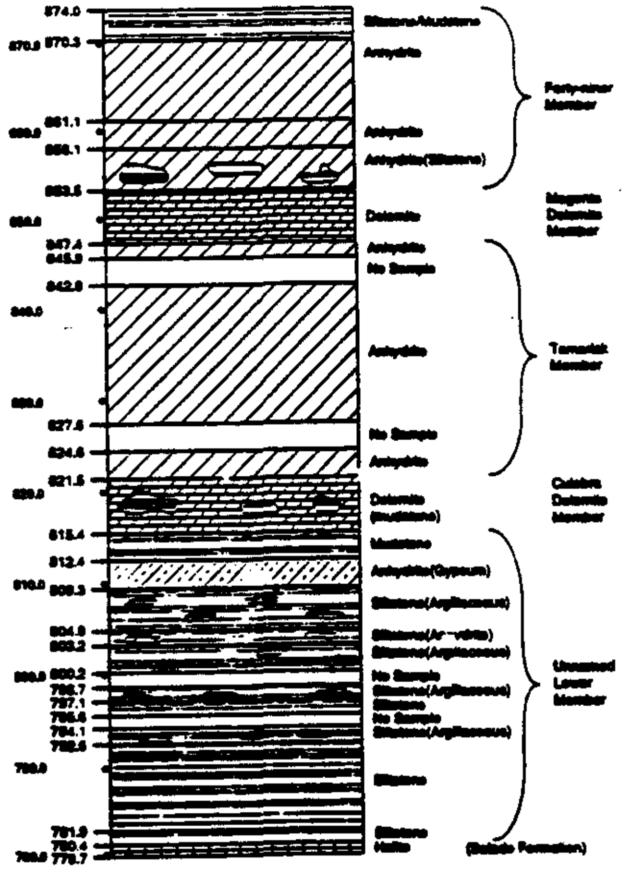


Figure 4-8. Detailed Lithology of Rustler Formation at ERDA-9 (reproduced from SAND92-0700/3; after SNL and USGS, 1982)

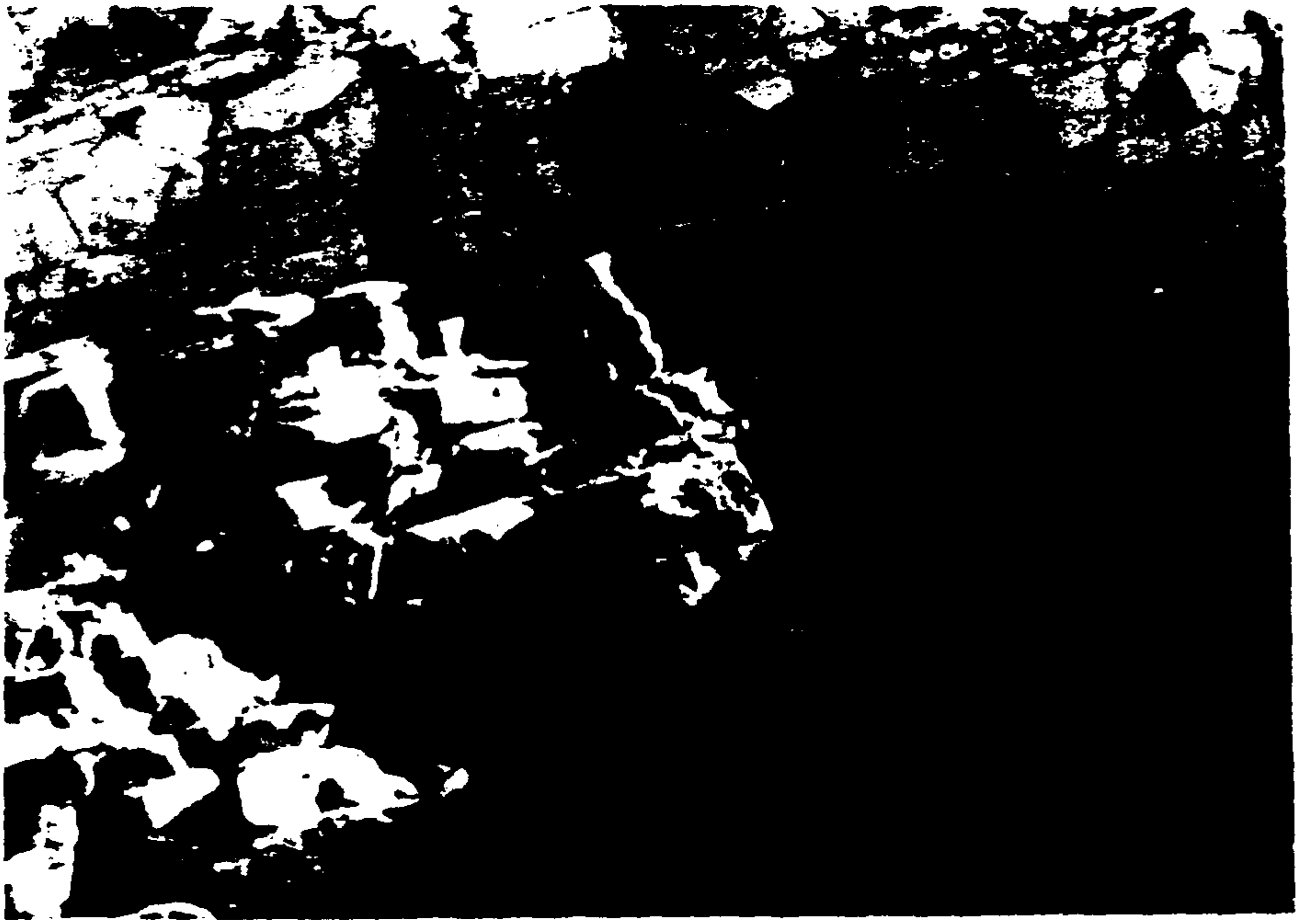


Figure 4-9. Outcrop of Culebra Dolomite Member of the Rustler Formation Where Removal of Underlying Halite Has Caused Fracturing (reproduced from Mercer, 1983)

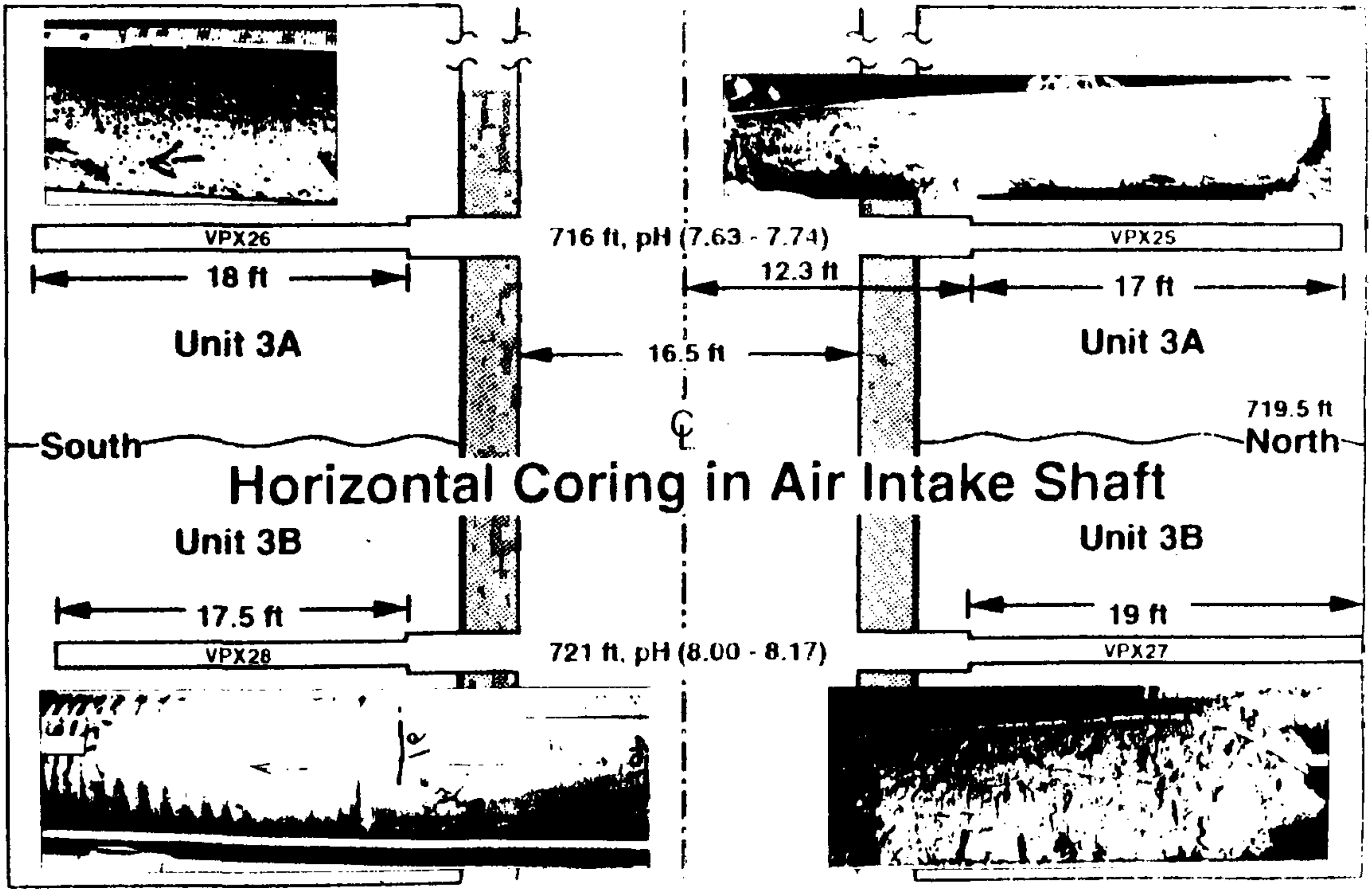


Figure 4-10. Horizontal Cores Removed from Culebra Units 3A and3B (Within 55 ft of each other horizontally and 5 ft vertically) in the Air Intake Shaft at WIPP. This modified figure was part of a October 20-21, 1992 presentation to the NAS WIPP Review Panel by Fred Gelbard (SNL) and was supplied by Fred Gelbard for use in this PART report.

discussed later. Gelbard, in his presentations to the PART, indicated that (as can be seen by inspection of the cores in Figure 4-10) the nature of the four cores was quite different, as was the capability of the four coreholes to produce water; (VPX27 produced nearly all the water).

Variability is also verified by the Culebra hydraulic conductivity tests which show a six order of magnitude variation from east to west ($2x10^{-10}$ m/s at P-18 to $1x10^{-4}$ m/s in Nash Draw), as is discussed in SAND92-0700/2, 1992. Mercer (1983) lists values for transmissivity at twenty wells and eight values for storage. The twenty-three single-well hydraulic tests conducted at WIPP between 1983 and 1987 (Beauheim, 1987) added fifteen values at new locations and seven retest values (SAND89-0462, 1989). Other early testing in the Culebra is discussed in SAND89-0462, 1989. Hydraulic test information (e.g., transmissivities, storativity, fluid densities, transient and undisturbed freshwater heads with their uncertainties) is summarized in the form of tables and plots in Cauffman et al. (1990). The log hydraulic conductivity variation for the Culebra is shown in **Figure 4-11** from the 1992 PA (SAND92-0700/2), and the available data on transmissivities presented in Cauffman et al. (1990) is shown in **Figure 4-12**.

The interpreted potentiometric surface presented in the 1992 PA (SAND92-0700/2) was discussed in Subsection 3.2.2 (Figure 3-23). Cauffman et al. (1990) interpreted values of freshwater head (**Figure 4-13**) based on fluid densities and their estimation of when the pressure data (in the transient history recorded at the well) was representative of undisturbed conditions (**Figure 4-14**). LaVenue et al., 1990, also Cauffman et al. (1990) LaVenue and RamaRao (1992) discuss how hydraulic stresses since the summer of 1981 related to construction and testing (e.g., drilling and excavating shafts and boreholes, long running tracer and hydraulic tests such as at H-4) have resulted in the formation of what Haug et al. (1987) describe as a 7 km (4.2 mi) drawdown cone 33 m (107 ft) deep at the shafts and 12.2 m (39 ft) and 7.1 m (23 ft) at the maximum at H-1 and H-2 respectively. LaVenue et al. (1990), after updating some of the freshwater head estimates of Cauffman et al. (1990), produced an interpretation of the undisturbed freshwater head contours (**Figure 4-15**) that was the basis for initial Culebra dolomite model calibration efforts as well as for the current WIPP PA (SAND92-0700/2-3) pilot point method of generating seventy transmissivity realizations (LaVenue and RamaRao {1992}).

As discussed earlier, Siegel et al. (1991) summarize the hydrogeochemical studies of the Rustler Formation. Hydrochemical facies in the Culebra were discussed and presented earlier (Subsection 3.2.2, Figure 3-21) as was the fracture filling. The $^{234}U/^{238}U$ activity ratios that were the basis for the west-northwest paleoflow system postulated by Siegel et al. (1991) are shown in **Figure 4-16.**

Conservative tracer tests (e.g., convergent-flow and two-well recirculating) were performed at the H-2, H-3, H-4, H-6, and H-11 hydropads (i.e., locations where three to four wells are within tens of meters of each other) during the period from 1983 to 1988 (Jones et al., 1992). The results of preliminary interpretations of the H-2 hydropad tests and the H-3 and H-4 hydropad tests reported by Hydro Geo Chem (1986) and Kelly and Pickens (1986), respectively, are summarized and integrated with the interpretations of all the tracer tests completed in the Culebra to date in the report by Jones et al. (1992). This study examined various all or nothing (both homogeneous and heterogeneous) conceptualizations of double-porosity-fracture-matrix transport, single-porosity-fracture-only transport, or single-porosity-matrix-only transport and found that the best of the three models varied depending on the location. Results can be summarized as follows:

- double-porosity-fracture-matrix at H-3, H-6, and H-11 under the interpretation of a heterogeneous system or equally well as a horizontally anisotropic system,

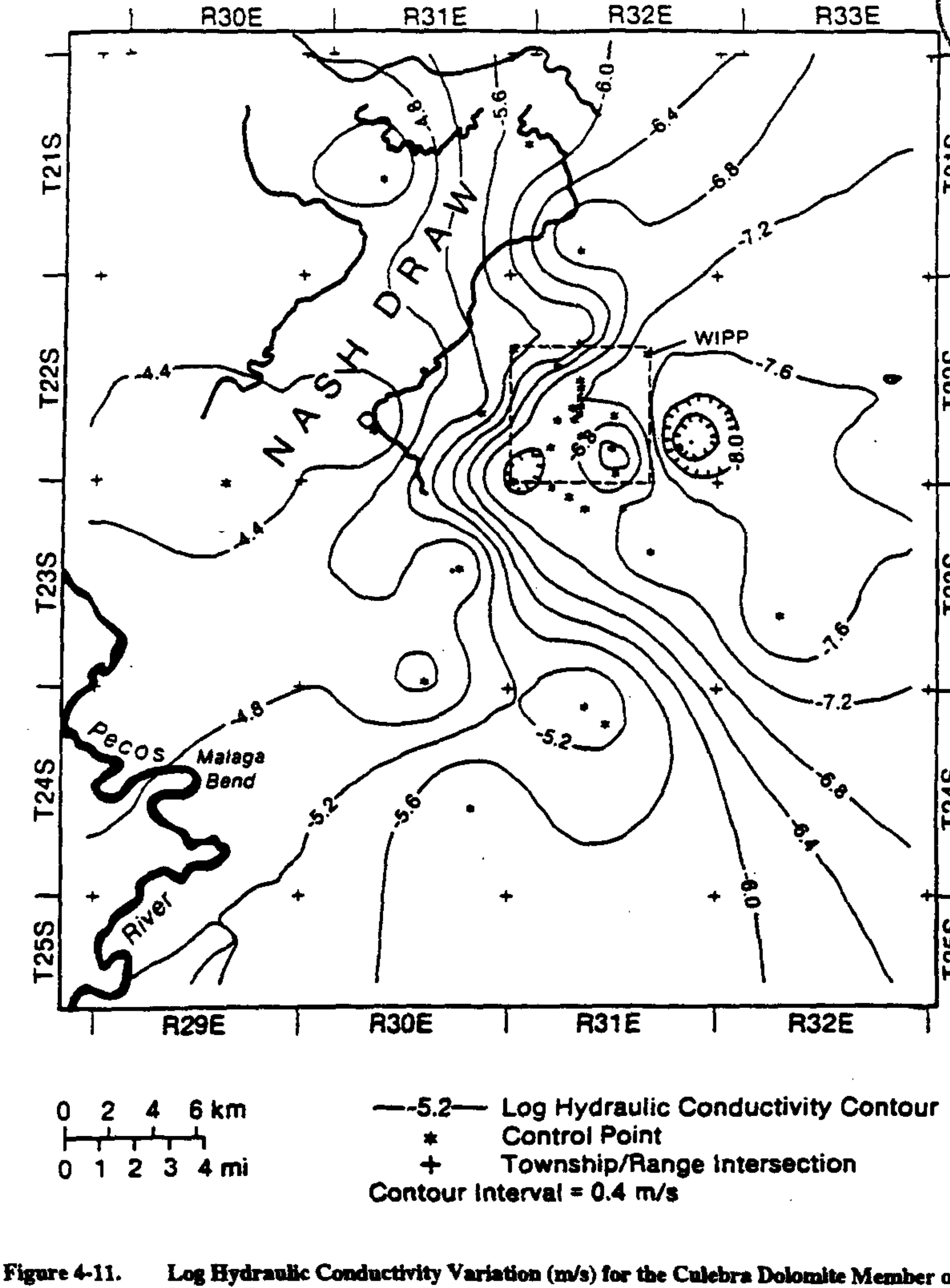


Figure 4-11. **Log Hydraulic Conductivity Variation (m/s) for the Culebra Dolomite Member of the Rustler Formation (reproduced from SAND92-0700/2; after Brinster, 1991)**

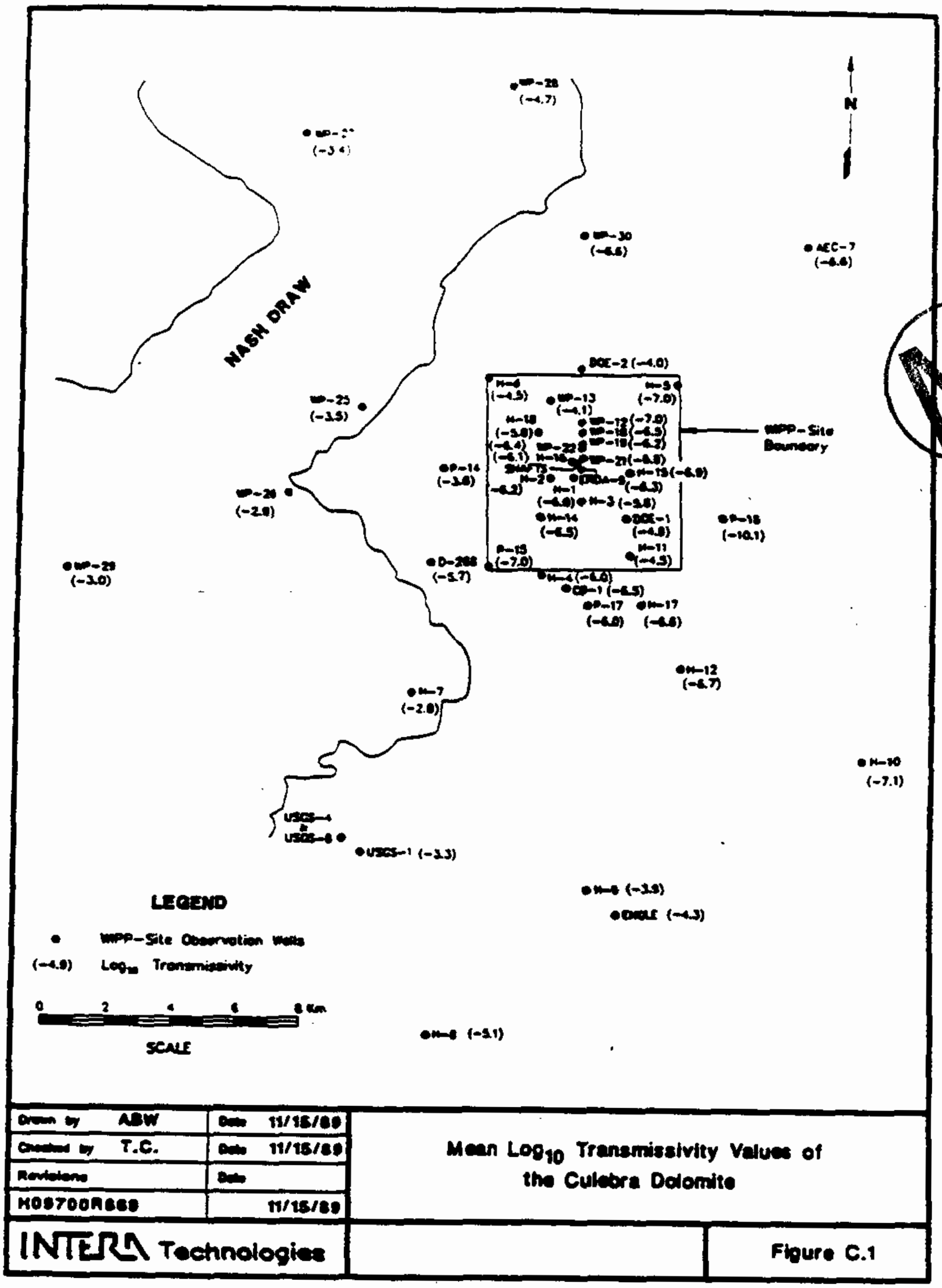


Figure 4-12. Calculated Culebra Mean Log_{10} Transmissivity Assigned at Each Borehole in m^2/s (reproduced from Cauffman et al., 1990).

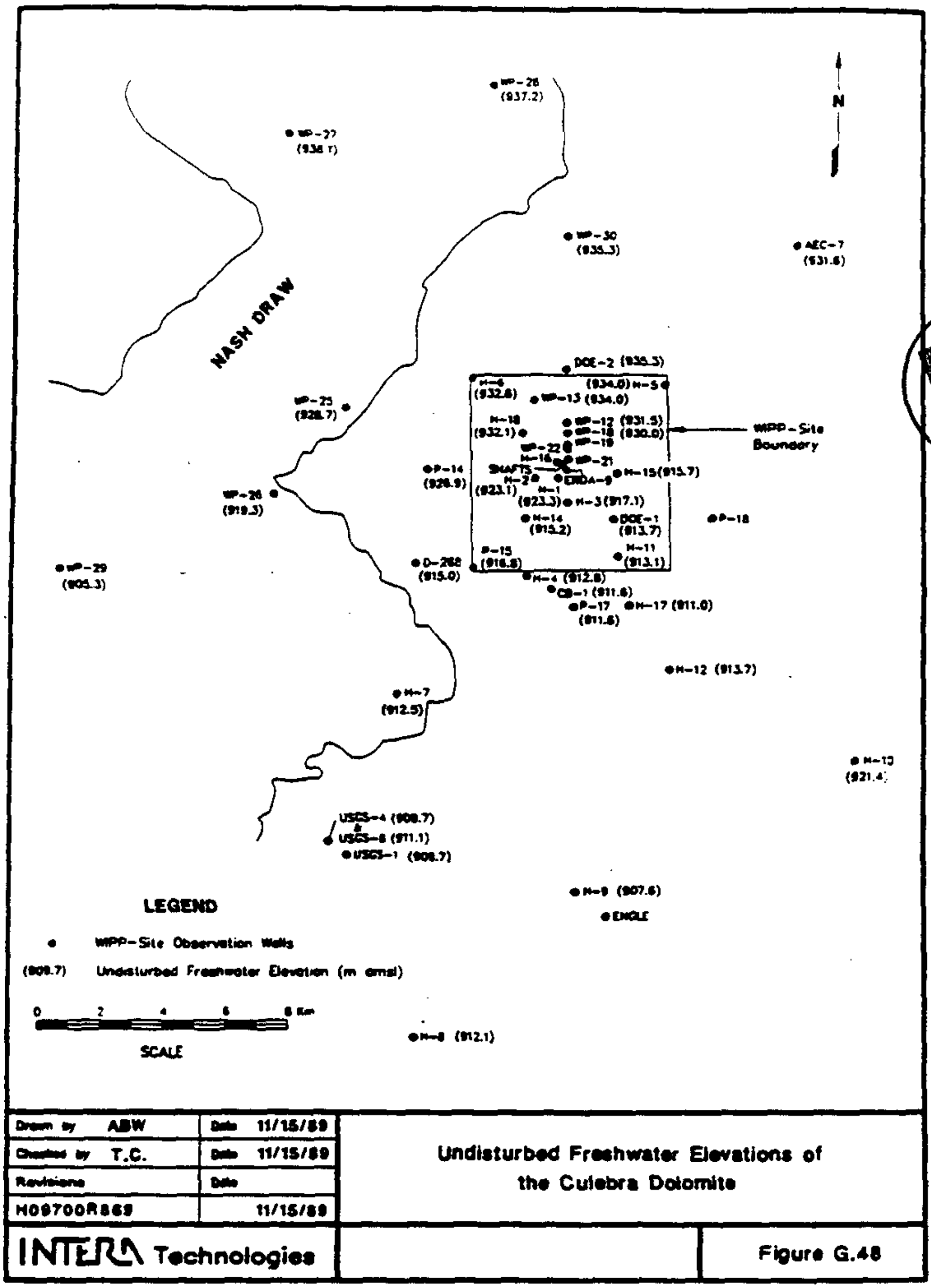


Figure 4-13. **Estimates of Undisturbed Freshwater Elevations in the Culebra at Each Borehole in Meters (reproduced from Cauffman et al., 1990).**

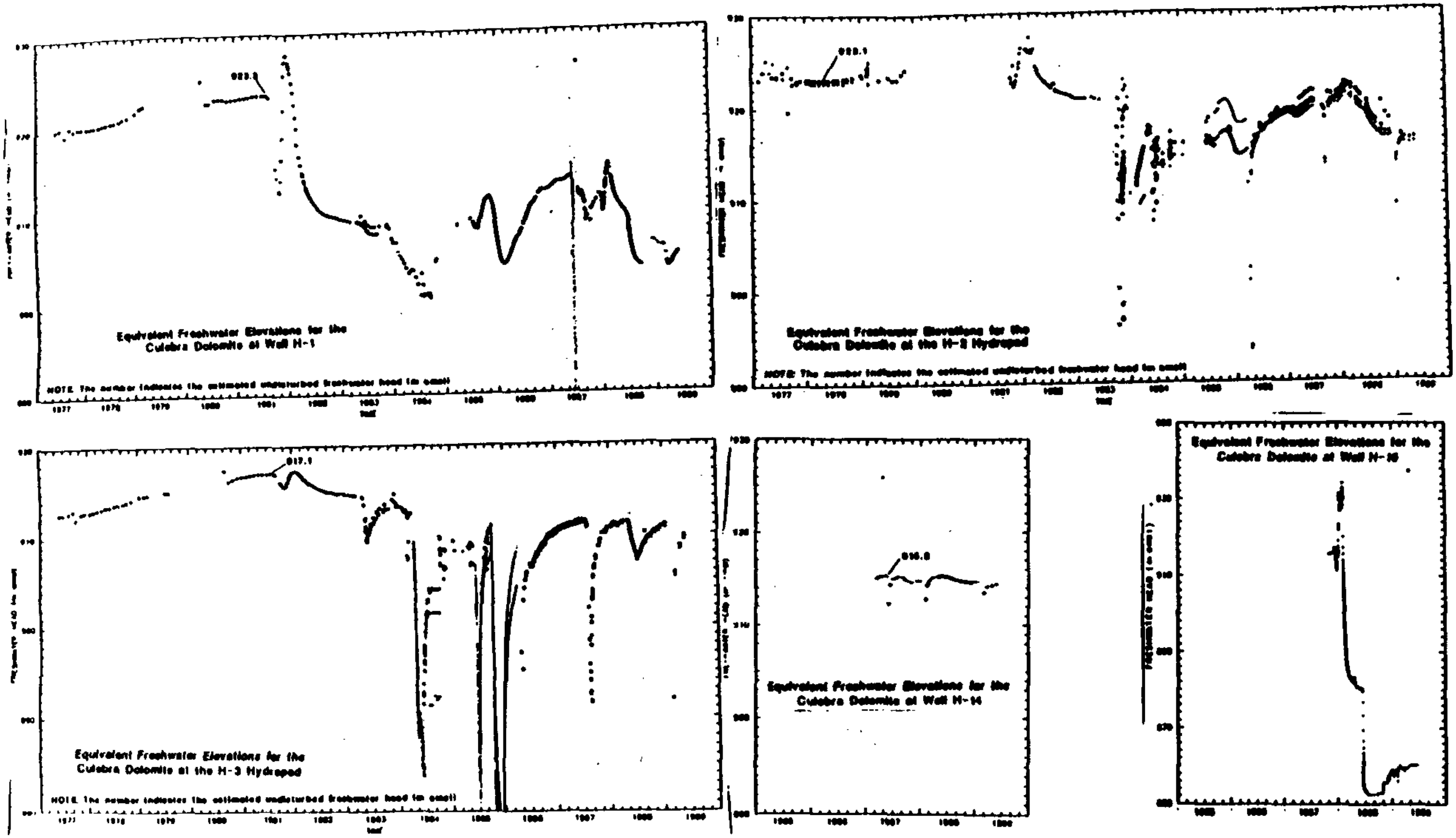


Figure 4-14. Example Transient Freshwater Head Hyudrographs for the Culebra Illustrating the Effects of WIPP Activities (reproduced from Cauffman et al., 1990).

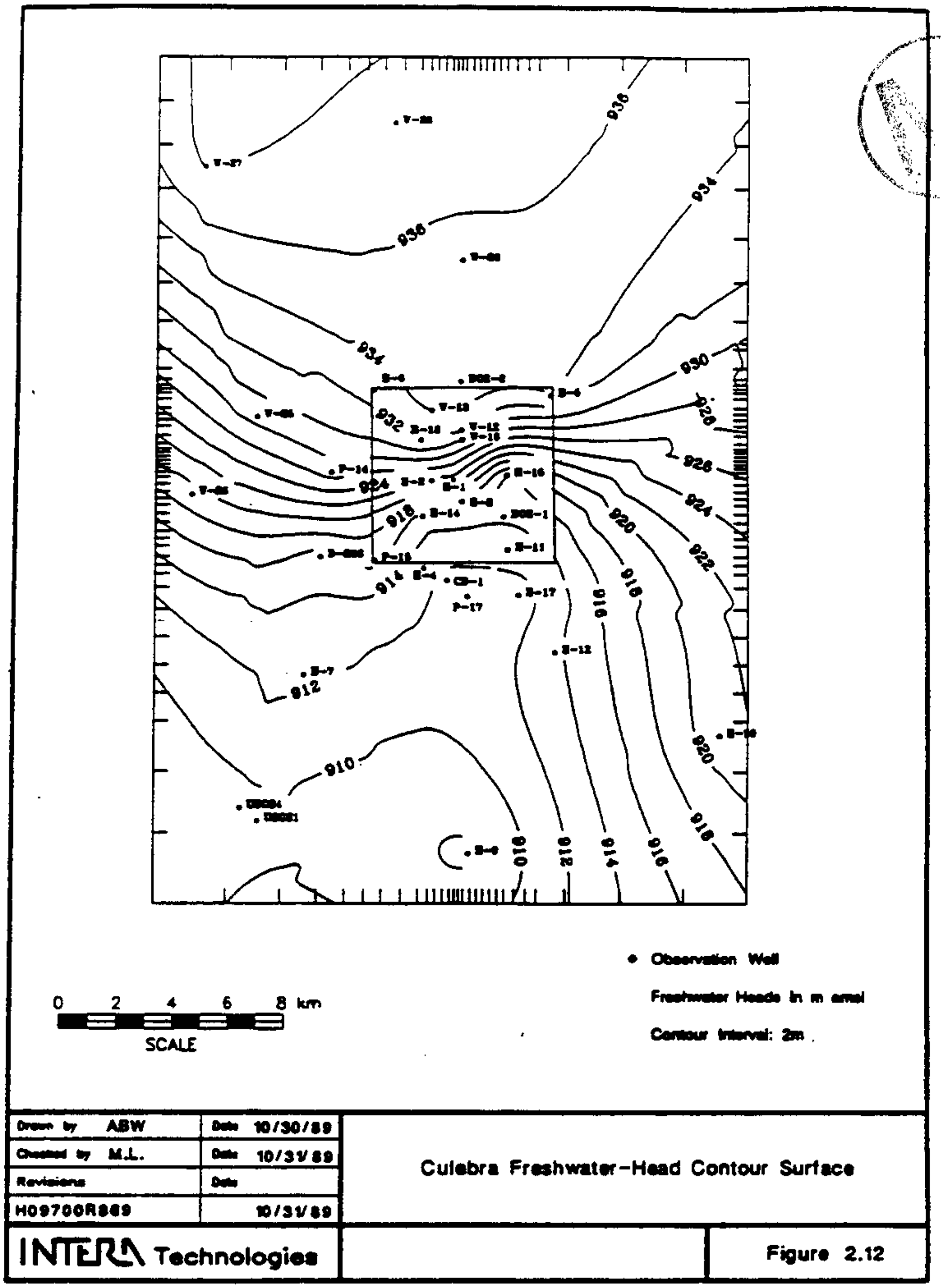


Figure 4-15. **Undisturbed Freshwater Head Contours in the Culebra Interpreted by LaVenue et al, 1990 (repreduced from LaVenue et al., 1990).**

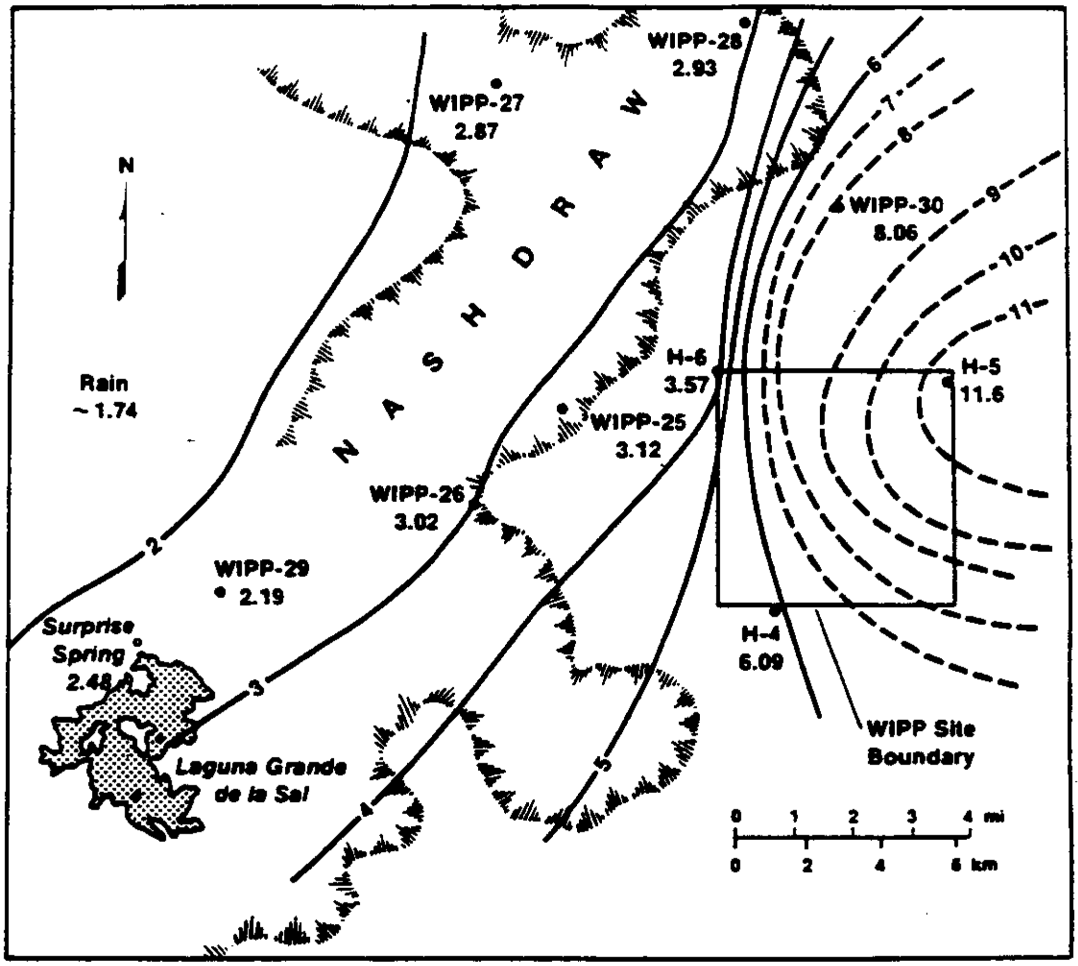


Figure 4-16. Contour Map of the ^{234}U/^{238}U Activity Ratio in Groundwater from the Culebra Dolomite Member of the Rustler Formation (reproduced from Siegel et al., 1991 from Figure 5.11 from Lambert and Carter, 1987).

- homogeneous single-porosity-matrix-only most representative at H-2 and inadequate at H-3, H-6, and H-11, and
- single-porosity-matrix-only through a vertically heterogeneous system the most representative at H-4 and inadequate at H-3, H-6, and H-11.

Jones et al. (1992) additionally conclude that a double porosity representation seems the most consistent with the observations (e.g., the large matrix porosities, 0.03 to 0.30) and that, as a result, matrix diffusion is an important process. They also point out that while observed tracer test behavior has been successfully simulated with the double-porosity-fracture-matrix model, other conceptualizations are possible and should be assessed. It should be pointed out, as discussed in the 1992 PA, that no fracture porosity measurements have been made. Interpreted values by Kelly and Pickens (1986) from the tracer test interpretations range from 1 x 10^{-3} to 2 x 10^{-3} (SAND92-0700/2, 1992).

4.3.1.3 Tamarisk Member

The Tamarisk Member of the Rustler Formation varies in thickness between 8 m and 84 m (26 ft and 273 ft) (36 m {117 ft} at WIPP) and is composed of three distinct layers (SAND92-0700/2, 1992) whose thickness may reflect lateral variations in deposition or dissolution. In areas unaffected by dissolutioning (Figure 4-5), the lower anhydrite layer, the thick middle section of halite and minor siltstone (sometimes polyhalite), and the upper anhydrite layer (Snyder, 1985) act as a confining unit (Mercer, 1983). In areas that may have been affected by dissolutioning of the evaporites, the Tamarisk exists in various intermediate states that affect both its volume and its other physical and hydrologic characteristics; (e.g., in Nash Draw only a few meters of residues of the original Tamarisk remain). Attempts to measure the permeability of this "water producing" unit at H-14 and H-16 (Figure 3-14), whose undisturbed hydraulic heads have never been successfully measured (Lappin et al., 1989), were abandoned when it was concluded that the transmissivity of the unit is too low to measure on the time scale of days (Beauheim, 1987).

4.3.1.4 Magenta Dolomite Member

The Magenta Dolomite Member of the Rustler Formation varies in thickness between 4 m and 8 m (13 ft and 26 ft) (6 m {19.5 ft} at WIPP) and is a distinct purplish-red (magenta) rock contains minor crossbeds as well as laminae of anhydrite and dolomite (Figure 4-6-b; Snyder 1985). Hydraulic conductivity (**Figure 4-17**) ranges over five orders of magnitude from 5.0 x 10^{-10} to 5.0 x 10^{-5} m/s (SAND92-0700/2, 1992). This variation, according to Mercer (1983) and Snyder (1985), is caused by the vertical movement of the rocks below the Magenta. This movement, as discussed earlier in Subsection 3.2.2.1, is related to either a collapse process, whose magnitude varies with the amount of dissolved halite, or an expansion process, whose magnitude varies with the amount of hydrated anhydrite.

The interpreted potentiometric surface presented in the 1992 PA (SAND92-0700/2) was discussed in Subsection 3.2.2.1 (Figure 3-24). While no porosity measurements have been made 0.20 has been assumed for interpretation of well tests (SAND92-0700/2, 1992). TDS of the Magenta range from 5,460 mg/l to 270,000 mg/l (Mercer, 1983). Comparisons of the Magenta to the Culebra indicate that

- Magenta generally has lower hydraulic conductivity (approximately two orders of magnitude), as discussed in SAND92-0700/2, 1992;

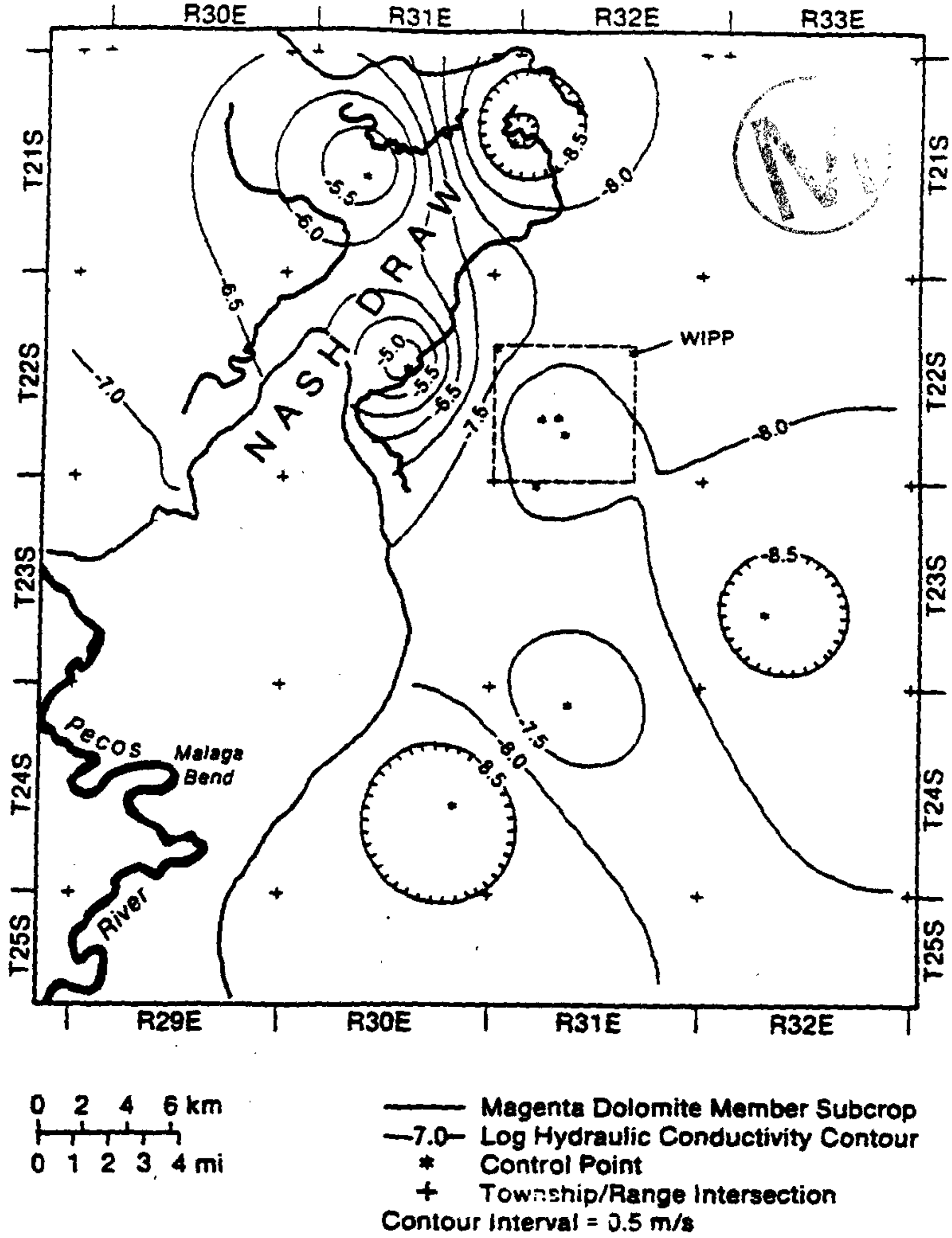


Figure 4-17. Log Hydraulic Conductivity Variation (m/s) for the Magenta Dolomite Member of the Rustler Formation (reproduced from SAND92-0700/2; after Brinster, 1991).

- Magenta generally has higher heads with the differences increasing eastward (LaVenue et al., 1990); and
- TDS in the Magenta is generally lower (Mercer, 1983).

4.3.1.5 Forty-Niner Member

The Forty-Niner Member of the Rustler Formation is a relatively uniform 20 m (65 ft) throughout the WIPP area (SAND92-0700/2, 1992). It is composed of three distinct layers consisting of a lower thick, light-to-medium-gray anhydrite bed, a middle reddish-brown silty halite or claystone unit, and an upper thick, light-to-medium-gray anhydrite bed (Snyder, 1985). Hydraulic conductivity tests at H-14, H-16, and DOE-2 yielded estimates of 5.0×10^{-9} m/s, 5.0×10^{-10} m/s, and 4.0×10^{-10} m/s, respectively for the medial claystone, (SAND92-0700/2, 1992; LaVenue et al., 1990).

4.3.2 Planned Activities and Issues

As part of the test program, two sets of activities are currently planned for the Non-Salado (as used here, the rocks that overlie the Salado host rock) portion of the natural barrier (DOE/WIPP 89-011 Revision 1, 1993). These two activities are outlined from Table 5.1 of DOE/WIPP 89-011 Revision 1 (1993) below.

- The Non-Salado Hydrologic Properties Activity includes
    - Core studies of rock properties (plan in preparation)
    - Regional-scale transport and sensitivity studies
    - Model development
    - Field testing and data interpretation for hydrology (planned)
    - Regional geochemical studies
    - Data base for field studies
    - Validation and international collaboration for model
    - Verification of performance-assessment model
    - Identification of potential underground sources of drinking water (in progress)
- The Non-Salado Transport Activity includes:
    - Adsorption studies
    - Radionuclide Solubility and Speciation
    - Brine mixing and radionuclide coprecipitation for the Non-Salado
    - Empirical sorption studies
    - Column experiments
    - Long-core tracer tests (plan in preparation)
    - Colloid characterization and transport
    - Test design and interpretation
    - Data base for performance assessment
    - Sorbing/retarding tracer tests
    - Data base laboratory studies

    - Non-sorbing tracer tests

Before discussing these activities and their relevance, it is important to review the current Culebra PA model assumptions, outline the basis and issues these activities were designed to address, and examine the issues identified by the PART.

4.3.2.1 Current Culebra PA Model Assumptions

The current Culebra PA model (summarized from SAND92-0700/2-3, 1992) assumes perfectly confined two-dimensional horizontal flow with no recharge from above or loss to units below. *Note that this implies it is isolated hydrologically and geochemically and thus unaffected by any of its surrounding units in the Rustler Formation.* Recharge is assumed to occur only to the northwest and north at presumed outcrop recharge areas. Climate change is accounted for by a transient variation in the Dirichlet boundary condition along these northwest and northeast boundaries. "The Culebra Dolomite Member is imagined to be a sheet-like mass of rock having lateral dimensions of the order of tens of kilometers and uniform thickness of 8 meters" (Figure 4-1, the box labeled 10). This sheet-like rock mass is envisioned as containing planar fractures that are all parallel to the plane of bedding and run continuously throughout the rock mass (**Figure 4-18**). The fractures are partially lined with clay in half of the realizations and are unlined in the other half. Advective transport is only accounted for in the open fracture space (i.e., no *advective flow in the matrix or clay fracture filling*). However, *one-dimensional diffusive interaction* with the fracture filling and the rock matrix is assumed. Material properties are assumed to be heterogeneous or vary from one material region to another, but within a given material region the material properties are assumed constant. While the system is envisioned as fracture flow, it is modeled as an equivalent porous medium. Hydrodynamic dispersion can be quantified by a Fick's law term. Adsorption of solutes in the solid phases obeys a linear isotherm, and there is always local chemical equilibrium between solutes and solid phases.

4.3.2.2 Test Phase Activities Basis and Issues to Be Addressed

The test phase plan (DOE/WIPP 89-011 Revision 1, 1993) indicates that from a compliance perspective the ability of rocks above the Salado (in particular the Culebra dolomite) to control, minimize, or eliminate waste release to the accessible environment must be demonstrated. The uncertainties in the current long-term performance predictions of the Culebra that need to be addressed are identified in the test phase plan and they are outlined below.

- Conceptual flow model uncertainty related to the appropriateness of the current conceptual model assumptions over the long term include:
    - the applicability of two-dimensional flow,
    - whether groundwater flow is in equilibrium with the boundary conditions,
    - whether vertical flow with other units of the Rustler Formation can be neglected, and
    - the applicability of pump test data over the long-term.
- Pump test data are not fully analyzed.
- The effect of climate change on model boundary conditions are not yet determined.

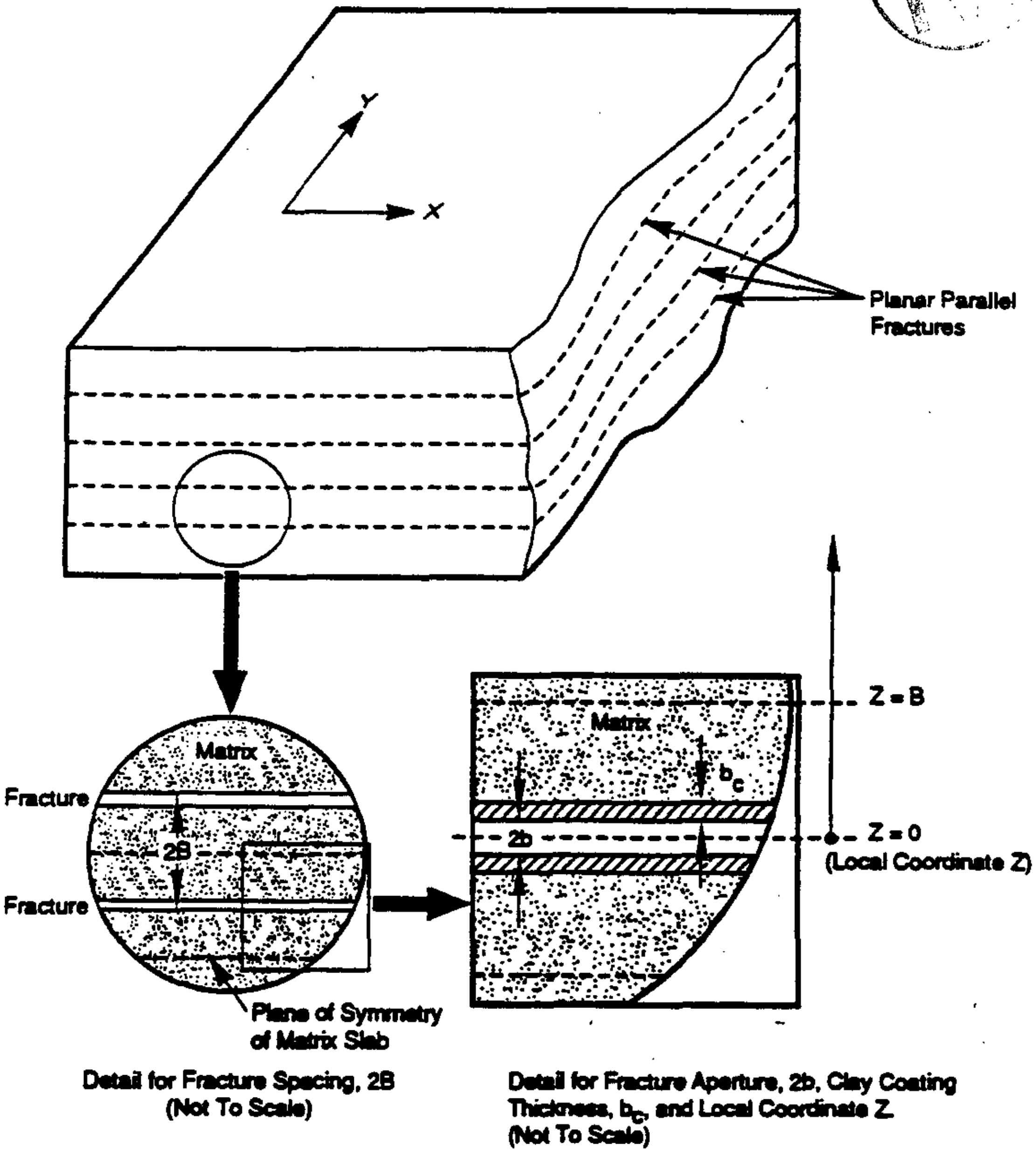


Figure 4-18. **Conceptual Hydrologic Model of the Culebra Dolomite Member (reproduced from SAND92-0700/2, 1992).**

- The confined aquifer model is not consistent with geologic, geochemical, and isotopic information.
- The effects of gas entry into Culebra have not been evaluated.
- Heterogeneity in flow properties and the associated scale-up uncertainty are not yet assessed.
- Conceptual transport model uncertainty exists, related to the appropriateness of a double porosity transport model (thought best to describe transport in the Culebra) that accounts for both
    - physical retardation by diffusion of radionuclides into the 16% mean porosity dolomite matrix of the Culebra, and
    - chemical retardation.

The test phase plan also indicates that there is a need to address the uncertainty related to whether "colloids containing radionuclides, if shown to occur, could inhibit both physical and chemical retardation."

The issues to be addressed by the activities outlined above are summarized here as a series of questions from the test phase plan.

1) Is the groundwater system in steady state or in a transient response from the last pluvial period?
2) Will groundwater flow rates change in the future?
3) Are the effects of vertical leakage and variations in groundwater flow negligible?
4) Can and do boreholes outside WIPP affect groundwater flow at WIPP (Figure 1-11)?
5) Are current conceptual flow models consistent with the site characterization data (particularly geochemical data)?
6) How would projected waste-gas releases associated with various scenarios affect flow in the Culebra?
7) What uncertainty would arise in the flow predictions from severe heterogeneity or hidden features?
8) Are there potential sources of drinking water in the regulated area of WIPP ?
9) Over what scale is a double porosity model relevant?
10) If a double porosity model is not relevant, what model should be included and what are the long-term transport implications of the other possible models?
11) If a double porosity model is relevant, how good is the case for this conceptual model?
12) What physical retardation can be expected without chemical retardation?
13) What chemical retardation can be expected with and without physical retardation for each brine and rock type along the probable flow path?
14) Can colloids exist in Culebra brines?
15) How would colloid formation and transport affect retardation?
16) How would waste-generated gas affect radionuclide retardation in the Culebra?

4.3.2.3 Issues Identified by PART

In order to achieve the quality of "reasonable expectation of compliance" there must be consistency in the way information is used to make interpretations to prove points and justify assumptions. Based on the PART's limited review of the information presented in the 1992 PA and some small fragment of the supportive literature on the WIPP site natural system, there appear to be many apparent inconsistencies that are not fully explained and many questions that arise about how conclusions were reached. Consider the following examples.

- In an attempt to explain the ^{234}U/^{238}U activity ratios (Figure 4-16) Siegel et al. (1991), postulated a paleoflow system flowing from the outcrop recharge areas in Nash Draw from the west-northwest potentially up the topographic gradient, which is usually the driver in a wet environment, while Bachman (1985) postulates surface streams during Gatuna time flowing from the northeast, (Figure 3-26) which are consistent with the topographic gradient.
- There are discussions of slumping related to halite removal in underlying units that are expected to cause vertical movement, and thus vertical fracturing of the Culebra dolomite and swelling related to gypsification of underlying and overlying anhydrites. However, the modeling only conceptualizes bedding plane fractures (Figure 4-18) without addressing the vertical fractures, both of which are expected and are evident in the outcrop shown in Figure 4-9.
- Two new "water producing" units have been identified since Mercer (1983), and yet, as discussed above (Subsection 4.3.1.4), undisturbed heads have never been successfully measured in one of these units, and attempts to measure the permeability were abandoned because its permeability is too low.
- Interpretations of tracer tests (Subsection 4.3.1.2) indicate that double-porosity-fracture-matrix at H-3, H-6, and H-11 is an adequate model under the interpretation of a heterogeneous system or as a horizontally anisotropic system; a homogeneous single-porosity-fracture-only model is most representative at H-2; and finally a single-porosity-fracture-only model through a vertically heterogeneous system is most representative at H-4. However, the 1992 PA states that a dual-porosity transport model provides the most realistic estimate. The visual examination of the cores from the waste shaft (Figure 4-10) would seem to support the tracer test interpretations; (i.e., possibly each of the proposed models applies somewhere).
- The undisturbed potential map for the Culebra has a drop in head of 18 m (58.5 ft) within the 6.4 km by 6.4 km (3.84 mi by 3.84 mi) land withdrawal boundary (Figure 3-24), yet in the same area a 7 km (4.2 mi) drawdown cone (see Subsection 4.3.2.2 and the hydrographs in Figure 4-14) is projected to be 33 m deep at the shafts in the Culebra and 12.2 m and 7.1 m (40 ft and 23 ft) at H-1 and H-2, respectively. These somewhat inconsistent results make determination of groundwater flow direction tenuous.
- The totally confined no-vertical flux concept for the Culebra modeling is inconsistent with studies by Davies (1989) and Haug et al. (1987) that support the vertical flux concept.

Based on this limited review and evaluation, there appears to be a basic interpretational issue that needs to be resolved. For example, the middle unit of the Tamarisk Member of the Rustler Formation (mudstone/halite) is interpreted to be continuous and is described as a "water producing unit." However, all four attempts to measure the head and permeability of this unit have failed. Does this difficulty arise simply because of insufficient resources available for permeability measurements or only standard geohydrologic interpretations and extrapolation techniques are being applied to interpret a system that has been affected by a dissolutioning process that varies spatially? Is this an attempt to "cling faithfully ... to normal interpretations" (page 5 of LeGrand's March 13, 1985, letter to Robert H. Neill of EEG in Chaturvedi and Channell, 1985)? In the context of a system that may be cyclically exposed to dissolutioning, there may be no simple classification of an aquifer and aquitard, as the nature of these units can change related to their location in space and the particular stage of evolution in the "stop and go" flow driven dissolutioning process described by LeGrand.

Neither the 1992 PA (volumes 1-3) nor the supporting literature reviewed contains an overall integrated picture of the supra-Salado hydrologic system that weaves the available information, understanding, and efforts together in a way that supports the current Culebra modeling in a manner that the PART believes is necessary to demonstrate that there is a "reasonable expectation of compliance" to the decision makers, the regulators, and the public, should the results of the final quantitative comparisons so indicate. This does not mean or imply that much of the information (data, observations, and supporting experimental evidence) is not available nor that all outstanding potential issues need to be addressed. It simply means that there has not been, and there needs to be, a multidisciplinary effort to take available information, competing interpretations, competing conceptual models, and any supportive experiments and/or modeling and combine them to explain what is currently known (e.g., regarding current head distributions and flow directions relative to past conditions, geochemistry, recharge, dissolutioning). The team could also identify what is known well enough and why, what is not now known well enough, and, for these areas, what probably cannot be determined and what needs to be determined.

4.3.2.4 Discussion of Planned Activities

As has been discussed, planned experiments and activities should be compliance-based. Therefore, the emphasis on planned experiments and other activities should be on those activities that are likely to resolve or significantly reduce the uncertainty surrounding important issues or on those activities that make a significant contribution toward achieving that qualitative goal of reasonable expectation.

In reviewing the test phase plan (DOE/WIPP 89-011 Revision 1, 1993) and the 1992 PA (SAND92-0700/1-3, 1992), and as discussed in the previous section, there is no integrated picture of the supra-Salado hydrologic system presented in either document or in any of the other documents reviewed. Most of the puzzle parts are there, but they have not been assembled in a way that makes it clearly evident what pieces are missing (i.e., what remains to be done). In this regard, the PART's examination of the list of non-Salado hydrologic properties and transport activities outlined at the start of this subsection gave rise to many questions. Consider the following:

- Why is it that colloids and colloid transport are mentioned as an important transport issue for Culebra only in the test phase plan? Where did this issue first surface? What is the basis (e.g., were there observations during tracer tests?), rationale, and justification for believing it to be important at all?
- Where was the compliance-based importance of Culebra gas flow modeling raised other than in the test phase plan (Section 5.1.1.3 page 5-8 of DOE/WIPP 89-011 Revision 1, 1993) and how is this relevant when it is not yet clear what the appropriate compliance model should be for water and solute? How is this more important than a modeling effort that considers density driven flow and communication between units of the Rustler?

For most of the non-Salado hydrologic properties and transport activities outlined at the beginning of this subsection, there is only the brief general description and justification found in chapter 5 of the test phase plan (DOE/WIPP 89-011 Revision 1, 1993). Of these activities, only the four indicated in this outline are in the actual planning stages. The 1992 PA (SAND92-0700/1-3, 1992) discusses just three of these activities: the batch and column radionuclide sorption studies and the seven-spot multiple well tracer tests being planned by Beauheim and Davies (SAND92-0700/1-3, 1992).

None of the draft planning documents were available for the PART review; however, the PART was briefed on the column retardation experiments being planned by Fred Gelbard (SNL) during one of the PART interviews, and the PART was able to visit the laboratory and examine the apparatus that will be used in these column experiments. The only other discussion regarding planned non-Salado experiments arose in the PART's discussion with EEG. Lokesh Chaturvedi expressed concern over the possibility that DOE might abandon the seven spot multiple well tracer tests for a series of five single well tracer tests, especially considering the extensive review that the seven spot experiments had received by the technical community outside WIPP.

The PART is not able to make detailed comments on any of the proposed experiments since it did not review them in detail. However, on the basis of the description of the planned column radionuclide sorption studies outlined by Fred Gelbard and the PART's discussion with EEG on the need to replace expert judgment data on Kd's with real laboratory information, these experiments appear to be compliance based and critical.

4.4 DEWEY LAKE REDBEDS

The Dewey Lake Redbeds do not represent a pathway for the migration of radionuclides, but control the flow of recharge to the underlying units of the Rustler Formation (SAND92-0700/2).

As described by Mercer (1983) and Snyder (1985), the Dewey Lake Redbeds conformably overlie the Rustler Formation. They are the youngest Permian age rocks in southeastern New Mexico and they mark an abrupt change in the depositional environment of the area from the dominantly evaporitic Rustler deposits to a deltaic sequence representative of a tidal flat or very shallow water deposits. These deposits consist of alternating, laminated to thin, even beds of reddish-brown siltstones interbedded with minor claystones and containing lenticular interbeds of fine-grained sandstone. Nearly all siltstones and claystones contain veins of secondary selenite gypsum, except near the top. While most of the veins are parallel to the horizontal bedding, many veins cut the formation at various angles as noted by occasional vertical veins observed in cores. The formation thins from east to west as a result of post-Permian erosion and varies in thickness from 167 m (543 ft) a few miles southeast of the site to 148 m (481 ft) near the center to 30 m (97.5 ft) a few miles to the southwest. The formation outcrops in low bluffs along the north and east of Nash Draw, where it is nearly completely absent except in sinks and collapse features.

Drilling for areal geohydrologic evaluation indicated local zones of permeability but did not indicate the existence of any continuous zones of saturation, although local minor zones of saturation were observed at wells H-1, H-2, and H-3 associated with the interbeds of fine-grained sandstone (SAND92-0700/2, 1992; Mercer, 1983). Mercer (1983) believes that sand units near the top of this formation become localized perched or semiperched saturated zones dependent on the existence of favorable local recharge conditions. Several wells at the J.C. Mills Ranch (formerly the James Ranch) south of the site (T. 23 S., R. 31 E., section 6 and 7) drilled to depth of 94 to 212 ft produce water from the Dewey Lake Redbeds (SAND92-0700/2, 1992; Mercer, 1983). Mercer (1983) postulates that ranch wells are completed in one of these lenticular sand units and, further, that the extensive region of active sand dunes to the east of this area could be the recharge source for the perched water bearing units.

Mercer (1983) hypothesizes that the Dewey Lake Redbeds act as a protective cover that retards the dissolution of evaporites of the Rustler by restricting groundwater movement within the Rustler as a result of the perched character of the water in the lenticular sands. However, he offers no explanation of just how continuous recharge would not eventually bypass these lenticular units by running off in very localized areas near a low end of these saturated lenticular units on their way to a continuously saturated unit like the Rustler in order to proceed to a regional discharge area. He does offer support for his hypothesis by arguing that groundwater percolating through the Dewey Lake Redbeds and penetrating to the upper anhydrite of the Rustler at WIPP should cause it to be altered to gypsum but that existing cores and geophysical logs do not indicate any alteration except where the Dewey Lake is thin or absent.

Hydrologic properties of all the supra-Rustler rocks are poorly understood because of the difficulty of making measurements and, as a result, have only been estimated based on the description of fine grained-sandstone and siltstone (SAND92-0700/2, 1992). Saturated hydraulic conductivity is estimated as 10^{-8} m/s and porosity is estimated as 0.2 (SAND92-0700/2, 1992).

5.0 IMPACT OF REPOSITORY AND WASTE EMPLACEMENT

In this section, the impact of repository excavation and waste emplacement on the long-term performance of the disposal system is considered. At first glance, the impact might be considered to be minimal because of the depth of the repository and the presence of only four man-made pathways (the shafts). However, the mechanical, hydrogeological, chemical and thermal fields will be disturbed by repository excavation and the introduction of waste, and changes in one field may cause changes in another, i.e., coupling. Assessment of the impact of these changes is complicated by questions of scale, both temporal and geometric. The time scale required by regulation (10,000 years) is too long for the usual iterative approaches, and the geometric scale is too large for experimental validation of repository response models. Natural heterogeneity of the rock mass and the influence of brine and gas generation are additional complicating factors.

The processes expected to occur in the repository following closure, and the PA efforts to understand and predict these processes are examined in this section. Subsection 5.1 provides background information on excavation effects and room closure. In Subsection 5.2 the permeability, pore pressure, and brine inflow in the disturbed rock zone are discussed. Subsections 5.3 and 5.4 examine gas generation and gas flow, and Subsection 5.5 considers the coupled effects of closure and fluid flow on repository behavior.

5.1 EXCAVATION EFFECTS AND ROOM CLOSURE

5.1.1 Introduction

Before considering the effects on the repository of excavation and emplacement of waste, this subsection will briefly review the undisturbed state of the Delaware Basin. There are four primary fields of interest: mechanical (stress-strain-displacement), hydrogeologic (pressure, regional pressure gradient, and velocity), chemical (species, concentration gradients, reactions), and thermal (temperature, temperature gradient, heat flow).

Prior to excavation, the stress field in the Salado is expected to be lithostatic and isotropic, because of the age of the basin and the observation that halite cannot sustain a stress difference without flowing to alleviate it. The hydrogeologic field is expected to have pore pressures close to lithostatic (because of the ductile nature of the salt), relatively low horizontal gradients (because of the location of the WIPP site relative to the edge of the basin), and very low velocity (because of the small gradients and the permeability of the halite). Because of the age of the basin and the small amount of mass transfer into the basin, one would expect that the chemical field would be near equilibrium with concentration gradients occurring only near the clay seams, anhydrite stringers, etc. Therefore, chemical reactions would not appear to be likely in this environment. The thermal field is expected to have a temperature of about 27° C and relatively low thermal gradient and high heat flow because of the relatively high thermal conductivity of rock salt.

All four of these fields will be disturbed by the excavation of a repository and the introduction of waste. The mechanical field will be altered by the excavation of the openings with attendant stress concentration around the openings, resulting in higher strain rates and displacements that tend to close the openings. A rather large sink is created in the fluid pressure field which is suddenly dropped to approximately one atmosphere at the periphery of the openings. This results in a rapid change in the pore-pressure gradient field, with an accompanying change in the velocity field and flow into the openings. The excavation process and emplacement of waste introduces new chemical species into the formation, which produces concentration gradients and the potential for reactions, particularly in the presence of brine. As the excavation develops, a ventilation system is installed which transports vapor from incoming brine to the surface. The accompanying temperature changes near the room surfaces results in a change in the stress field, but it is unlikely that the thermally-induced strain will be large enough to induce surface fractures in the halite because of the relatively low initial surface temperature of the rock.

The discussion above implies the coupling of phenomena, i.e., changes in one field may cause changes in another. For example, the excavation-induced disturbed rock zone (DRZ) is likely to have both higher porosity and permeability than the far-field rock. Modeling of coupled phenomena is difficult due to the lack of complete understanding of the coupling and appropriate data. In PA it is desirable to make bounding calculations using relatively simple, uncoupled models. However, it appears to be prudent to understand coupled phenomena that may invalidate assumed bounding models. WIPP PA generally avoids making bounding calculations and promotes the probabilistic approach as required to capture and evaluate uncertainty, Beauheim et al (1993).

5.1.2 Questions of Scale

Some of the most difficult and challenging aspects of designing, licensing, and constructing nuclear waste repositories revolve around questions of scale. The time scale required by regulation, 10,000 years, is too long for the usual iterative approach of "build and test and redesign" used in developing common engineered systems. It is not possible to develop a pilot plant and observe its performance through its life cycle in order to improve future designs. The remaining options include conservative design, in which driving forces are overestimated and the ability of the repository to contain waste is underestimated. Even this conservative approach cannot guarantee adequate performance of the repository because the failure of engineered systems is sometimes caused by unanticipated loading conditions, for example, the dramatic failure of the Tacoma Narrows Bridge caused by dynamic wind-structure interactions that were not accounted for in the design. In the case of repositories, the possibility of overlooking a potentially important failure scenario or interaction is minimized by careful design and analysis, PA, and the licensing or certification process.

Complementary to the conservative approach outlined above, is the development of computerized models to simulate the future performance of the repository system. Given the circumstances, this is the best that can be done. It is necessary, but not sufficient, that these models reliably simulate observations made during various laboratory field tests at WIPP. Finally the judgment of experts and probabilistic modeling can be used to assess the performance of the system relative to the regulations. These approaches appear to be the best possible, given the time scale and uncertainty of the problem.

In addition to the time scale, there are geometric scale problems. The geometric scale is too large for experimental validation of repository response models. **Figure 5-1 A and B** illustrates observations made of trough subsidence over mined excavations. In part A, the width of the excavation is less than the depth, and there is an arching effect present that transfers part of the load

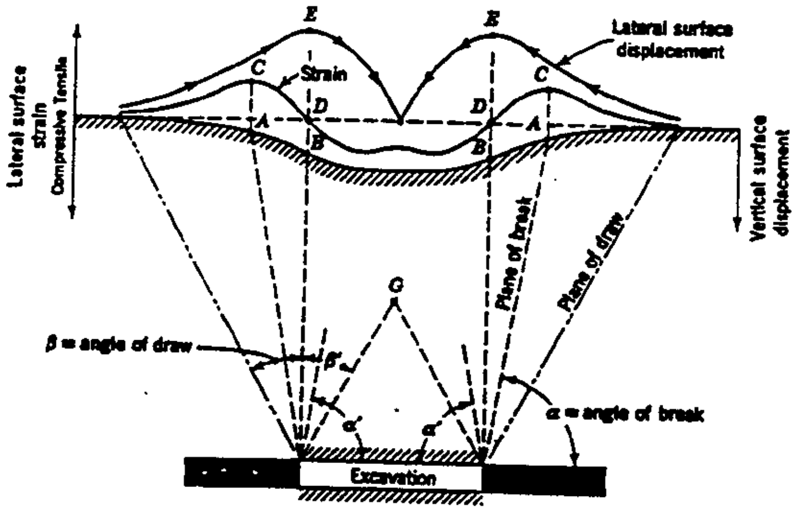


Fig. 18.2.2. Idealized representation of trough subsidence. (After Rellensmann[1]).

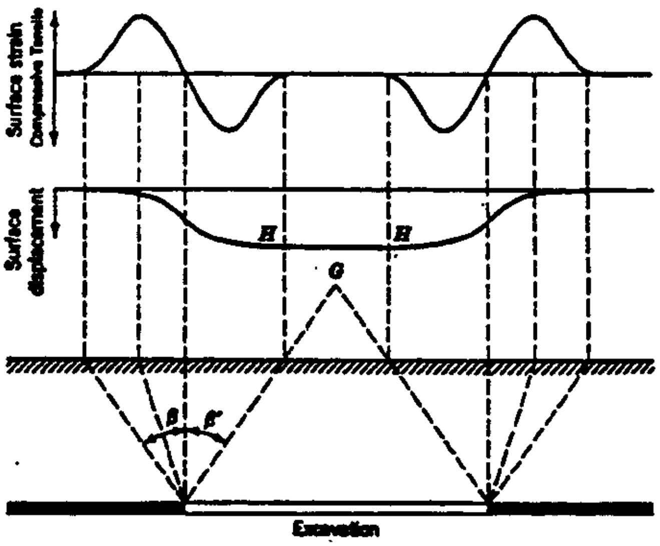


Fig. 18.2.4. Supercritical subsidence. (After Denkhaus.[2])

Figure 5-1. **(A) Idealized Representation of Trough Subsidence (after Rellensman, 1957) (B) Supercritical Subsidence (after Denkhaus, 1964).**

from the overburden to the undisturbed rock on both sides of the excavation. In this case mine pillars, which are located in the region marked "excavation" on the figure, do not need to carry the entire load of the overburden. This situation is termed subcritical subsidence. Part B illustrates supercritical subsidence where pillars near the center of the excavation must carry their share of the overburden load. Field experiments performed at the WIPP site are necessarily in a subcritical state because of the geometric scale problem, whereas the fully-developed repository will be approximately at the critical point. Large scale subsidence is not expected at the WIPP due to low extraction. Rather, this figure is shown to illustrate the problem of scale. Being able to predict room closure in the experimental area, using the elastic-steady state creep constitutive model with reduced elastic modulus in the code SANCHO as has been done in PA, may not ensure successful calculation of room closure in the full repository where the stress field will be different. This topic is further developed later in this section.

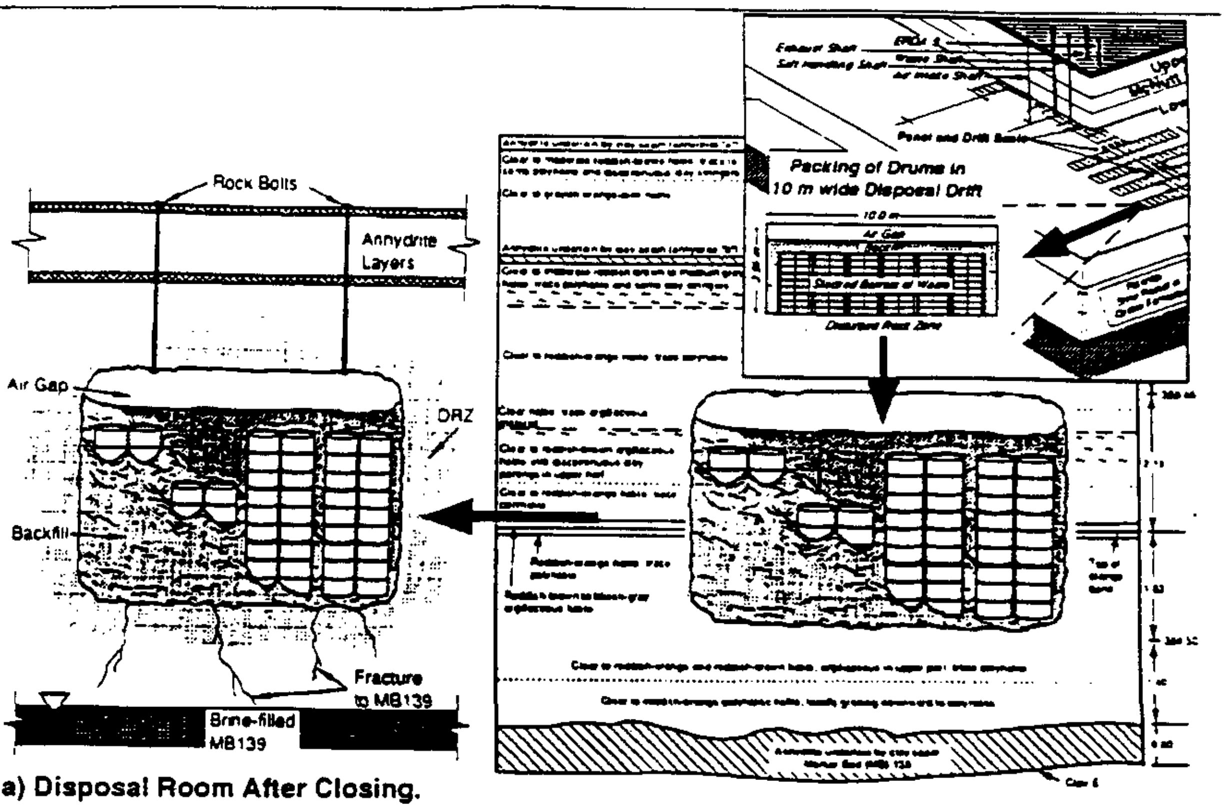
Again, it is necessary to rely on the ability to calculate and predict the future performance of the pillars and the rooms. The validity of these calculations cannot be directly checked because of the time and geometric scales. However, it is possible to validate the models over the period of observation and demonstrate that deformation (i.e., the change in size and/or shape of a region of the continuum) mechanisms in the near field around the rooms are consistent with those observed in salt naturally deformed over a much longer time. This procedure builds a higher degree of confidence in the simulated results, provided that the predicted loading conditions are approximately correct and a more complete constitutive model (described below) is used.

Work on a constitutive model for WIPP salt creep and room closure has gone on continuously since the late 1970s (Munson and Dawson, SAND79-1853, 1979; Munson et al., SAND88-2948, 1989; and Chan et al., 1992). This work is well respected in the rock mechanics community internationally and is representative of the state of the art. The Munson-Dawson (M-D) model has not yet been incorporated into PA calculations, SAND92-0700/3 DEC92 DRAFT, although plans exist to incorporate this work in the near future.

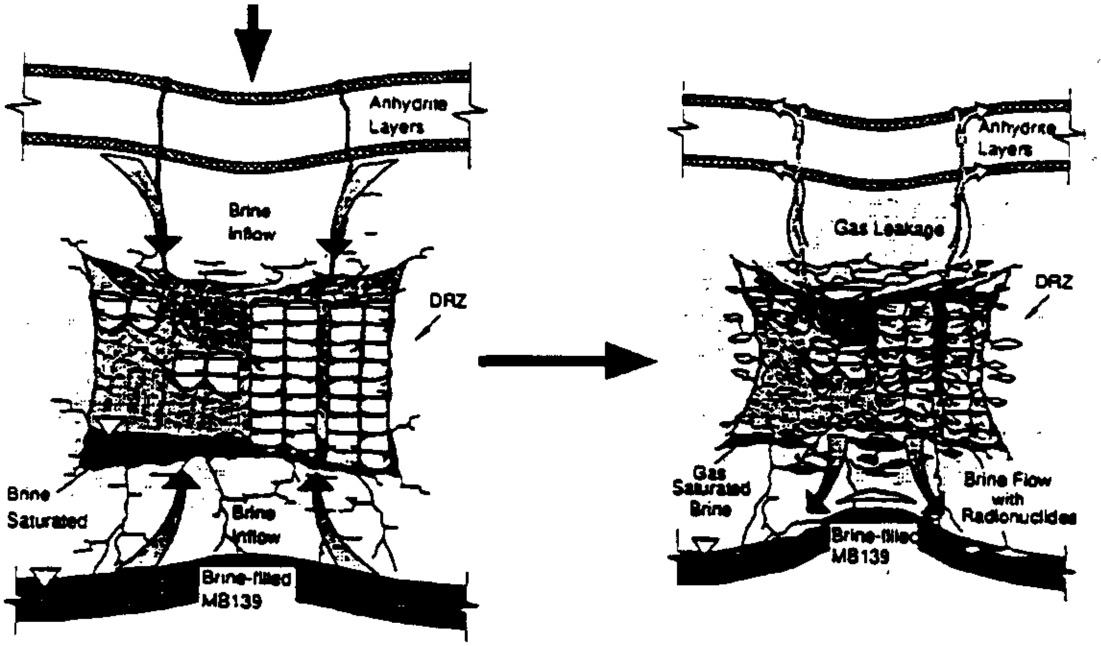
5.1.3 Heterogeneity: Natural and Repository Induced

One of the factors that makes modeling of observed phenomena in underground openings difficult is natural heterogeneity of the rock mass. Many roof falls and floor heaves seen in underground salt mines can be traced to a plane of weakness such as a clay stringer, anhydrite layer, or marker bed. These features sometimes exhibit spatial variability in properties and are frequently discontinuous in nature. **Figure 5-2** shows artists' conceptions of possible interactions between the closed disposal room and these heterogeneous features. These illustrations indicate interaction between natural heterogeneous features and the DRZ, which is a repository induced heterogeneity.

The rock bolts shown in Figure 5-2 help to maintain the structural integrity of the roof and, provided the bolts are tensioned, reduce the effects of the DRZ in the roof. Rock bolts are sometimes used in the ribs and in the floor to maintain the integrity and longevity of the opening, but not at WIPP. The effects of rock bolts are difficult to model when using two-dimensional models and are another example of repository induced heterogeneity.



(a) Disposal Room After Closing.



(b) Disposal Room After Room Creep Closure and Brine Inflow.

(c) Disposal Room After Possible Gas Leakage, Room Expansion and Brine Inflow.

Figure 5-2. **Diagram Illustrating the Conceptual Evolution of a Disposal Room Within a WIPP Waste Panel. Illustrated in the upper left is the setting for a typical disposal room relative to the stratigraphy at depth and the progression of states, starting with (a) an idealized depiction of the disposal room after closure; (b) the disposal room after creep closure and brine inflow, and (c) the disposal room after possible gas leakage, room expansion and brine inflow. (Reference 1991 PA)**

Another example of heterogeneity is the high pressure brine pockets in the Castile formation below the repository level. These brine reservoirs represent a potential source of brine that could affect salt deformation (Section 5.3), gas generation, and radionuclide releases, but are likely only if tapped by boreholes generated by inadvertent human intrusion. Heterogeneity is of crucial importance in compliance and is receiving needed attention (see DOE/WIPP 89-011, Rev. 1, Test Phase Plan for the Waste Isolation Pilot Plant, March, 1993).

5.1.4 Repository Environment

The repository environment will affect its subsequent behavior. Significant brine migration into disposal rooms would, for example, enhance salt flow (i.e., deformation that changes with time, Section 5.2). Temperature increases due to heat-generating waste are expected to be rather small, but salt flow is very sensitive to temperature. Gas generation and its timing relative to the creep closure of the room and the effectiveness of the man-made seals, particularly in the DRZ, could alter the expected response of the repository. Gas flowing into microfractures in the DRZ could promote more brittle behavior in the salt mass by reducing the effective confining pressure. Figure 5-3 from Chan et al., 1992 shows the influence of confining pressure on creep rate for a range of stress differences.

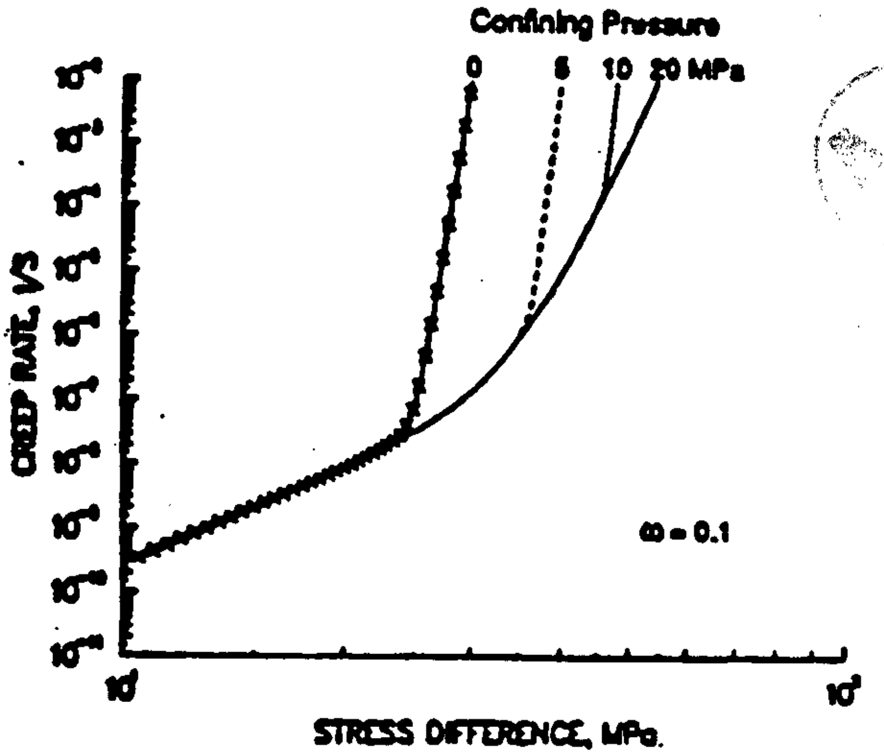


Figure 5-3. **Calculated Steady State Creep Rates as a Function of Stress Difference for Various Levels of Confining Pressure Showing a Reduction of Creep Rate with an Increasing Level of Confining Pressure (Chan et al., 1992).**

5.1.5 Current State of PA Relative to Creep and Room Closure

Creep and room closure PA process modeling is ongoing (**Figure 5-4 and Figure 5-5.**) Sandia National Laboratories will soon incorporate the M-D model in PA calculations. Currently PA is using an elastic-steady state constitutive model for salt in a code called SANCHO (Stone et al., 1985), that is simpler to incorporate and faster to calculate in SANCHO than the preferred M-D model. *The Test Phase Plan for WIPP, March 1993 indicates that the M-D will be used in future* calculations.

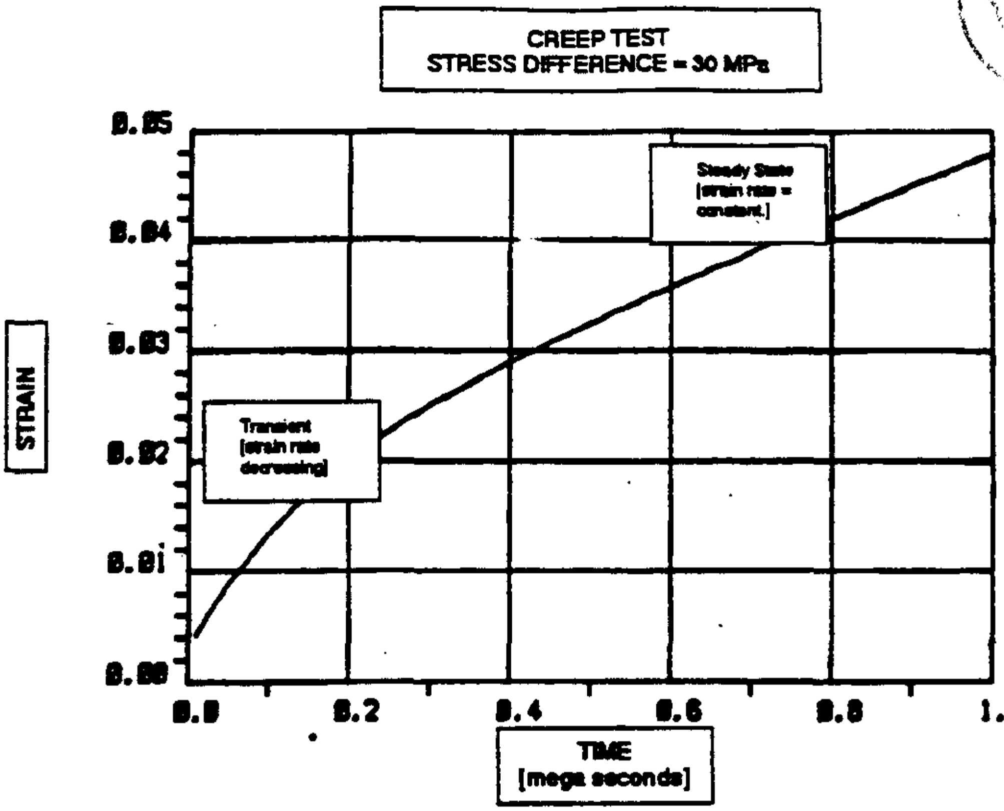


Figure 5-4 Typical Creep Test Showing Transient and Apparent Steady State Response.

The use of the M-D model in the calculations is important because decisions relative to the importance of certain events depends on when room closure and consolidation of the backfill and waste occur. Davies et al., 1991 present an overview of strongly coupled chemical, hydrologic, and simplified structural processes. **Figure 5-6** shows the dramatic reduction in cumulative brine inflow, the rate of brine inflow, and the slope of the curve (which actually reverses sign, indicating that brine is being displaced out of the room) when the coupling of gas generation and brine inflow to a disposal room is considered in the absence of room closure.

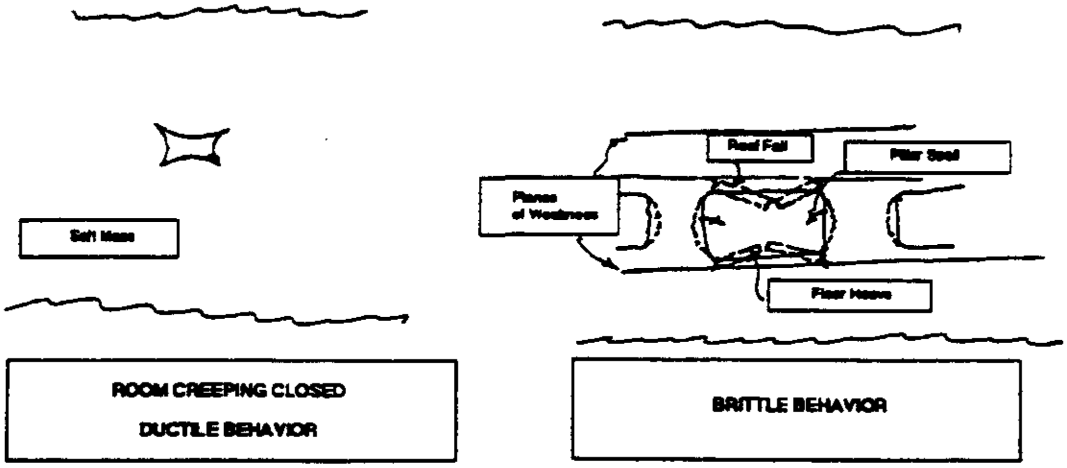


Figure 5-5. Schematic Diagram Illustrating Creep Closure by Ductile and Brittle Processes.

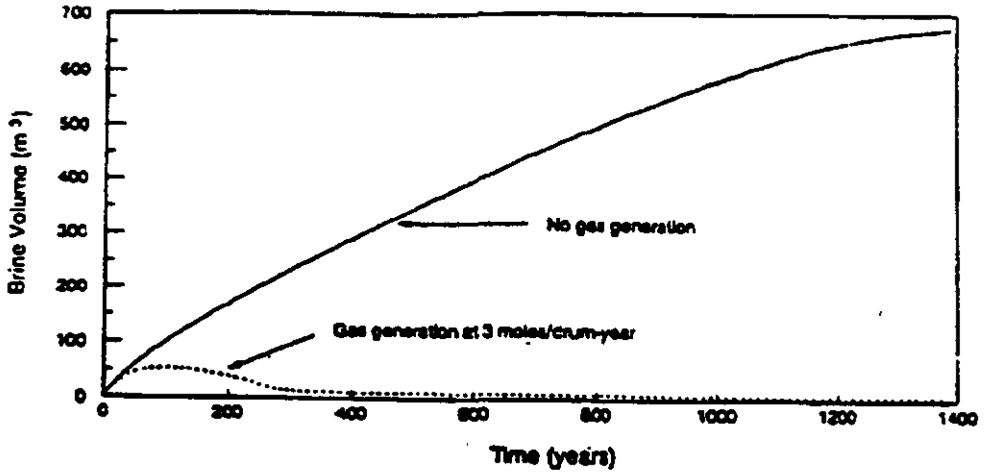


Figure 5-6. Plot Comparing Cumulative Brine Inflow to a Disposal Room in the Absence of Gas and Brine Inflow with a Fixed Gas-Generation Rate of 3 Moles per Drum Per Year. These simulations are based on the model configuration and parameters illustrated in Figure 7. (Davies et al., 1991).

If creep closure is considered without gas generation, average initial porosity of a backfilled room of 0.65 drops to 0.3 in 100 years and to about 0.16 in 750 years. **Figure 5-7** shows the porosity history for this case (Davies et al., 1991, Fig. 11). However, if constant gas generation rate exists in a perfectly sealed room, the decrease in porosity leads to higher pressure, which in this model leads to a reversal in room closure and an expansion of the room, as shown on **Figure 5-8.**

The results shown by Davies et al., 1991 are from two-dimensional calculations using the SANCHO code and the elastic-steady-state constitutive model. The elastic modulus in this simplified constitutive model was reduced in magnitude until computed room-closures agreed with measured values. Because the elastic modulus is a fundamental physical property of the salt, it has a measured value. When the value is changed to enhance agreement with measured results, it becomes a fitting parameter, and the constitutive equation has no fundamental basis. If the deformation in the repository is very similar to that of the measured results, such a model may be adequate to predict performance. However, it is difficult to have much confidence in the results of calculations using this model until it is shown that the simplified model produces results in agreement with the more realistic model.

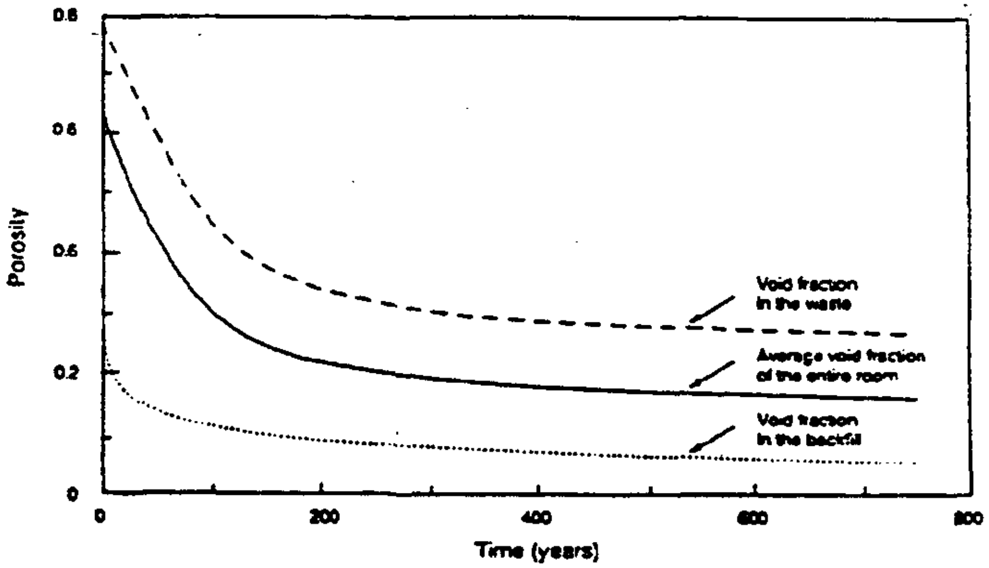


Figure 5-7. **Simulation of Average Porosity History of a Disposal Room Filled with TRU Waste and 70% Salt/30% Bentonite Backfill and no Gas Generation, Adapted from Butcher et al. in Press A (Davies et al., 1991).**

The finite-element mesh used is shown in **Figure 5-9** and has several limitations that may affect the results. For example, the model used is two-dimensional and represents one quarter of the room and pillar system; i.e., two planes of symmetry have been assumed, one vertical and one horizontal in a homogeneous salt mass. The horizontal symmetry plane forces the model to assume that the room is filled with waste surrounded by crushed salt backfill with no air-gap at the top. Further, the assumed horizontal symmetry plane makes it impossible to include some heterogeneity. No inter beds are included in the model.

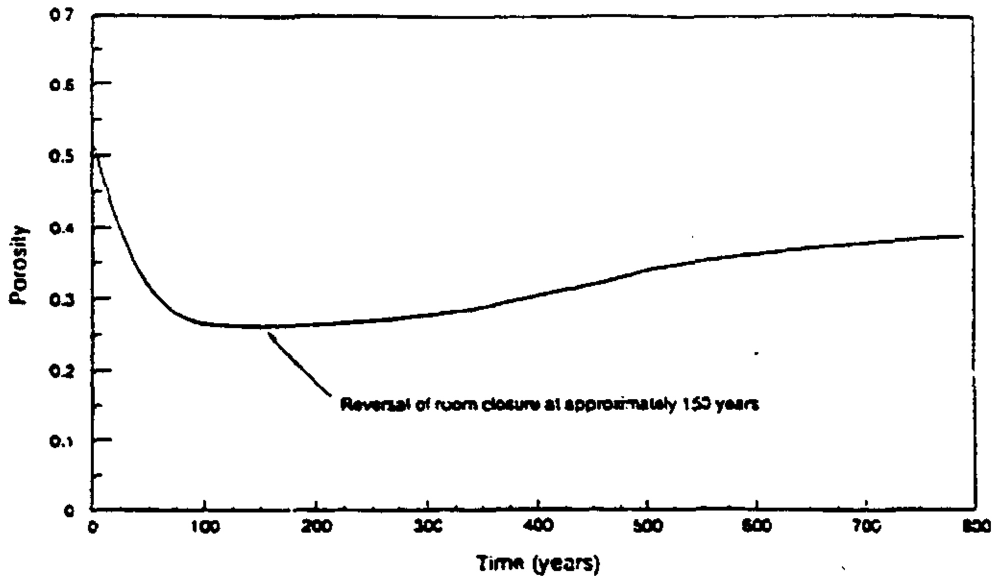


Figure 5-8. Simulated Changes in Average Room Porosity for a Perfectly Sealed Room with a Gas Generation Rate of 2.60 Moles per Drum per Year (Davies et al., 1991).

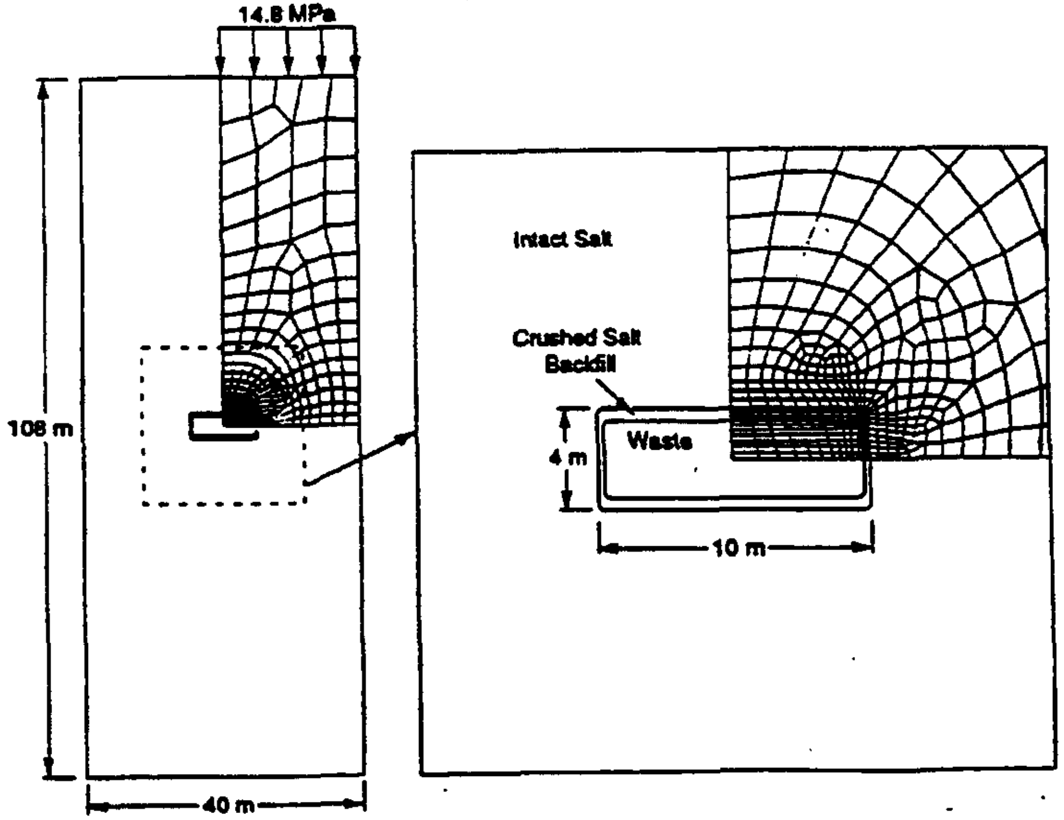


Figure 5-9. Modeling Mesh and Boundary Conditions for Calculation of Porosity Surface with SANCHO (adapted from Mendenhall et al., 1991, Figure 3-2).

This model is valid only if there is a continuing sequence of identical rooms in both horizontal directions, which there is not. In a repository with a width greater than critical width, see Figure 5-1, the model represents pillars near the center of the total width of the excavation.

With respect to loading on the room-pillar model, the overburden is represented as a fluid that only applies pressure to the top of the model; i.e., the model neglects the stiffness of the overburden and its potential effect on room performance. For rooms away from the central area of a repository of supercritical width, and for repositories of less than critical width, arching may occur in the overburden and the assumed boundary conditions may not be adequate. The model used also assumes that the rooms are all excavated and filled simultaneously, which is not the case. The time sequence of excavation, filling with waste, and backfilling with crushed salt may be important in the development of the DRZ and the response of the repository rooms.

The salt has been assumed to be homogenous and at a constant temperature; in other words, the natural thermal gradient, heat generated by the waste, heat removed by ventilation during the operating period, etc. have all been neglected. Given the known sensitivity of salt deformation rate to temperature, temperature calculations and thermal effects should receive careful consideration in PA.

SNL investigators are aware of the limitations of the model, as currently used. The coupled system is complicated and increasing the detail in the model will require significant effort; however the details of the system may be important to PA. It is apparent that further work in this area is needed for better understanding of the performance of the coupled system.

If chemical (gas generation), hydraulic, and structural effects are all considered simultaneously, increased gas pressure is expected to decrease brine inflow, which would limit the gas pressure generated, and decrease the possibility that the rooms would expand rather than close. If the gas pressure becomes too high, new fractures will be created that will lower the gas pressure. These fractures may occur in the DRZ if the gas-generation rate is high. It is apparent that the timing of each of these phenomena is important in the coupling. Also, the question remains of whether a disposal room can effectively seal the gas generated. The rate at which the DRZ fractures heal, relative to the gas pressure generated, appears to be important.

The M-D model and most other models are based on the results of laboratory scale tests in a dry environment. This may or may not be important, depending on how well the laboratory results scale up to the repository scale and how much brine actually enters the repository. Salt deformation may be affected by micro-cracking and gas pressure in the pores (Chan et al., 1992, report on work in progress to incorporate brittle phenomena into the M-D model). Finally, the M-D model has been developed using primarily the results of triaxial compression creep tests at various temperatures in the range expected in the repository. It is questionable whether any model based on simple stress paths will be able to accurately predict the response of the rock to the potentially more complicated stress path (possibly including a change from contraction to extension) that may occur in the repository. This is not a criticism of the M-D model; it is the best currently available and should be used. Ideally, the M-D model, as modified to include brittle behavior, will account for all of the deformation and will be adequate for coupled analysis. The Test Phase Plan for WIPP, March 1993, p. 3-27, notes that in referring to coupled multiphase studies, "these models describe the physical behavior of the disposal room in greater detail than necessary for the performance assessment. . . . The three-phase model may allow the Project to better understand and represent the relationship of room dynamics and fluid flow for the performance assessment."

5.2 THE DISTURBED ROCK ZONE

Brine inflow rates into the waste-filled rooms and other repository-level hydraulic properties of the Salado Formation are being characterized carefully, because brine

- is the principal means by which radionuclides may be transported out of the repository;
- strongly influences gas-generation rates and pressures within the repository; and
- generally affects mechanical properties of salt and salt seals.

Hydraulic conductivity (permeability) and specific storage (porosity, storativity) all increase, while fluid pore pressure decreases within 1 to 3 meters from the walls of the excavations (Beauheim et al., 1991). These changes are to be expected because in the course of mine closure, a large stress gradient is generated from lithostatic pressure within the salt to atmospheric pressure at the excavation boundary. This leads to rapid transient creep processes, including cracking at grain boundaries in the salt and faulting in MB 139 (**Figure 5-10 A**).

Munson et al. (1989) and Chan et al. (1992) have incorporated a creep damage model into the multi-mechanism deformation model proposed by Munson and Dawson (1984) in order to account for the transient response. Ratigan et al. (1992) have developed a criterion, based upon 45 tests on WIPP salt and 39 tests on Avery Island salt, whereby, at high strain rate and at critical ratios of shear stress to mean pressure in the salt, $\sqrt{J_2} / I_1 > 0.27$ positive volumetric strains occur by dilatancy. Damage due to dilatancy increases as the ratio $\sqrt{J_2} / 0.27 I_1$ increases above unity and for values less than unity, zero or negative volumetric strains are accompanied by crack healing. R.L. Thoms (personal communication, December, 1992), for his model of a solution-mined cavern within N. Dayton dome, found that the critical value of $\sqrt{J_2} / I_1$ was exceeded only within 3 meters of the wall at 850 meters depth. At WIPP, Borns and Stormont (1988) found that dilation within the DRZ, resulting from microcrack porosity, increases with time and is accompanied by increases in gas flow rate (by 10^4, **Figure 5-10 B**), apparent resistivity (by 900 ohm-m) and by decreases in compressional wave velocities (by 10%). This dilatant volume increase at least partly accounts for closure rates observed that are three times higher than those calculated prior to excavation; (see also Munson et al., 1989).

5.2.1 Permeability and Pore Pressure

Each year, as a result of new understanding and improving technology, the hydrologic properties of various members of the Salado have been refined (Beauheim et al., 1991; Howarth et al., 1991; Jensen et al., 1993a,b; PA, 1992). More specifically, estimates of far-field permeability have consistently decreased, while those of intrinsic formation pore pressure have increased as it has become clear that disturbances resulting from the excavation have strongly influenced diffusivities and hence the results. For far-field hydraulic properties, the most reliable data have come from fifteen boreholes drilled 23 meters deep in the vicinity of what was to become a 110 m-long by 3 m-diameter (309 ft-long by 11 ft-diameter) experimental tunnel termed Q. Jensen et al. (1993 a, b)

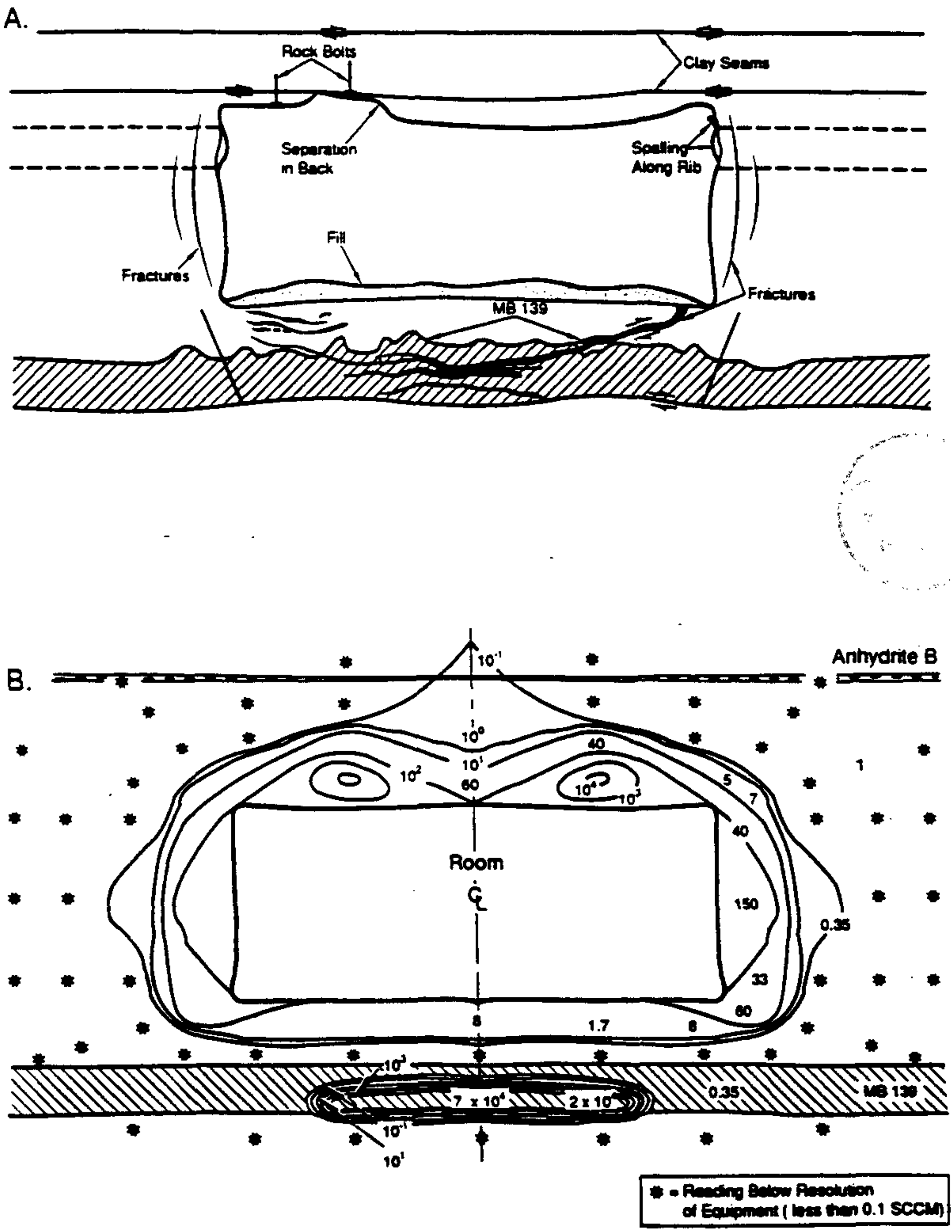


Figure 5-10. **Disturbed Rock Zone Adjacent to Underground Excavations at the Waste Isolation Pilot Plant. (A) Fracture Patterns. (B) Contours of Gas Flow Rate for Gas Injected at Less than 1 MPa (Davies et al., 1991).**

describe schedules, procedures and data acquisition in detail, and interpretations of pre-excavation data are given by Howarth et al. (1991) and Gorham et al. (1992). Howarth et al. (1991) used somewhat different data reduction, fitting, and interpretation procedures than did Beauheim in 1991 and Gorham in 1992, and, in some instances, permeability estimates differ.

Beauheim et al. (1991) discuss details of permeability tests in rooms C2, D, L4, 7, S0P01 and SCP01 (Figure 2-8) and conclude that since all tests except three were within 5.6 meters of the excavation walls, estimated hydraulic properties are likely to represent values from zones that have been disturbed or depressurized. Formation pore pressures within 3 meters of the wall range from 0.1 to 0.5 MPa. Pore pressure beyond 3 meters is variable, in the range 2.7 to 9.3 MPa and, beyond 6 meters, apparently is greater in the anhydrite (12.5 MPa) than in the halite; little change in permeability occurs in this depressurized zone (Beauheim et al., 1991; Gorham et al., 1992). Hydraulic conductivities within 3 meters of the wall are higher by two to three orders of magnitude for both halite and anhydrite layers. Peach (1991) also observed a thousand-fold decrease in permeability of Asse, Germany, salt from the gallery wall to 3 meters into the salt body in a mine room at the 800 m (2,600 ft) level.

Stormont et al. (1991) document significant increases in both brine and gas permeability in salt near a 3-foot-diameter "mine-by excavation" drilled into the floor of the WIPP mine. Prior to excavation, formation pressures and permeabilities were determined using an array of 4.8 cm (1.9-in) test holes drilled at distances of from 1.24 to 4 radii (r) from the center of the .45 m (1.5-ft) radius hole to be excavated. During and after excavation, the low pressure and high deviatoric stress near the wall induced major damage to the pore structure by cracking and dilation; large, transient pressure drops and increases in permeability were recorded in test holes placed at 1.25 and 1.5 r. These changes were much less pronounced in test holes at 2, 3, and 4 r, where little to no pore structure damage occurred (Stormont et al., 1991).

5.2.2 Brine Inflow

Mechanically, the limited brine in the DRZ may increase transient creep rates by enhancing crack growth rates at the low confining pressures (Brodsky and Munson, 1991). There is no evidence to suggest that dislocation processes (microplasticity) are enhanced by hydrolytic weakening in alkali halides, and pressure solution (grain boundary dissolution-diffusion-precipitation) kinetics at 27°C are such that these processes are not expected to contribute greatly to the creep strain during closure (Borns, 1987; Carter et al., 1993). However, the presence of water does enhance crack healing rates (Hickman and Evans, 1991; Brodsky, 1990; Costin et al., 1980) and hence the dilatant state of the DRZ during creep closure will depend on the balance between crack opening, and healing. Possible brine sources other than Salado include leaks through shaft seals of Rustler Formation brines (Section 7) and injections from boreholes in Castile Formation pressurized brine pockets; however, the Castile sources relate only to relatively late time frame behavior.

Brine inflow rates at WIPP have been monitored extensively in the Brine Sampling and Evaluation Program (BSEP) (Deal and Case, 1987; Deal et al., 1989; Deal and Roggenthen, 1992) and for rooms D, L4 and the Q access drift (Finley et al., 1992). **Figure 5-11** shows the size and orientations of 17 small-scale brine inflow boreholes relative to the stratigraphy of the waste facility horizon. Subhorizontal holes DBT 16 and DBT 17, were drilled into a single stratigraphic unit, clean

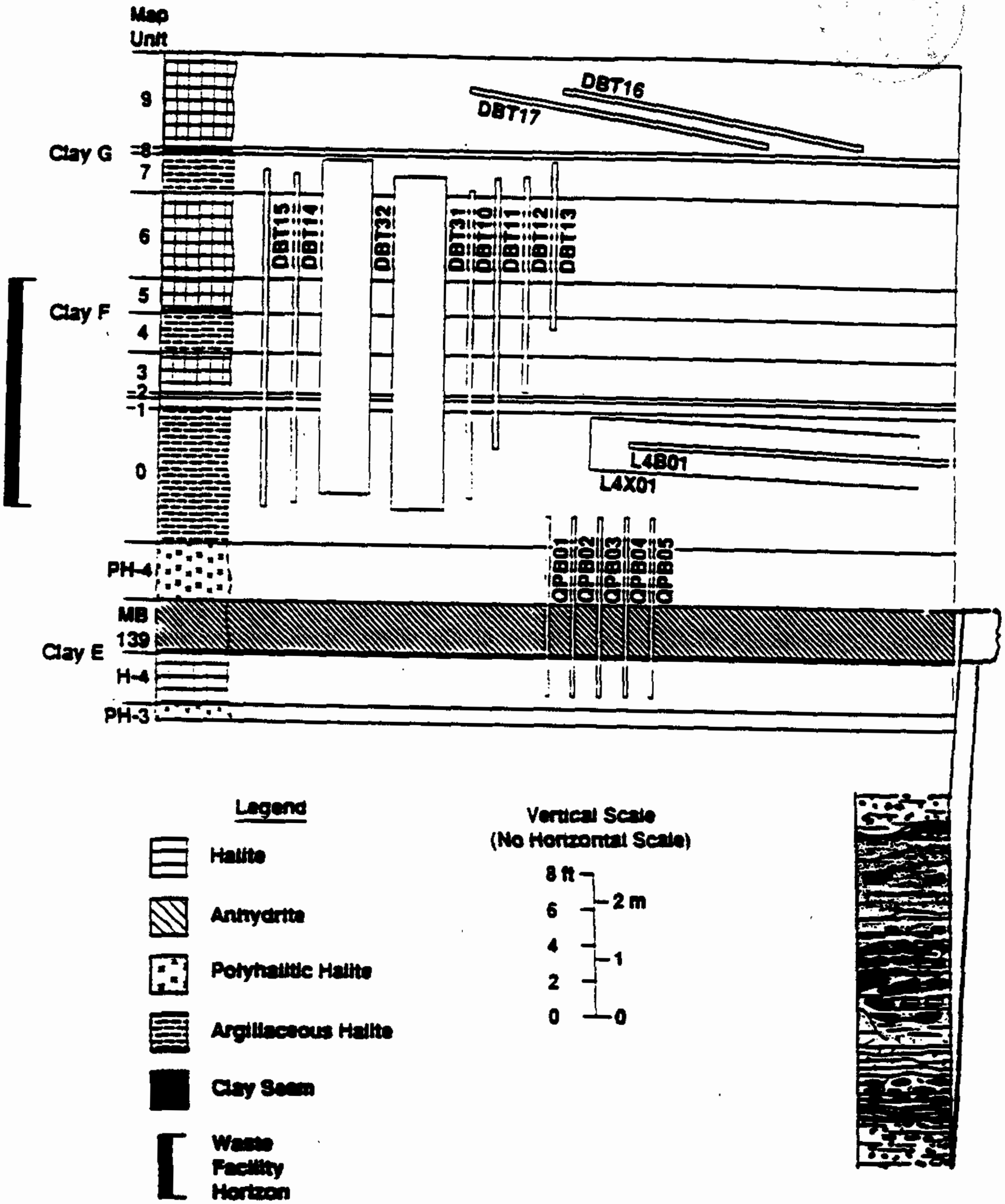


Figure 5-11. Schematic Diagram Showing Small-Scale Brine Inflow Boreholes and the Stratigraphy Tested in Each (Finley et al., 1991; MB 139 stratigraphy from Borns, 1985).

halite map unit 9, in the rib of room D and have shown no brine inflow in 1,350 days. The other two subhorizontal holes, L4X01 and L4B01 were drilled into map unit 0, a 2-m (6.6 ft) thick layer of argillaceous halite comprising the lower half of the waste facility horizon; these two holes have produced small amounts of brine over the monitoring period (Figure 5-12). Clay content, which is directly related to bulk water content (wt % H_2O=wt % insol. res./3; Stein and Krumhansl, 1989) is believed to be one of the controlling factors influencing the brine inflow. Deal et al. (1989) also find small inflow rates for horizontal holes of the BSEP program and note that such holes older than 2.5 years are not producing brine.

Brine inflow rates for vertical holes through the repository horizon are generally higher than for the subhorizontal holes. Rate of inflow for DBT 15 is shown in Figure 5-12 but these values differ appreciably from those recorded for hole DBT 14, a like-sized (10-cm-diameter) hole, 9 meters away, bored through the same stratigraphy. The cumulative brine mass for the eight boreholes in the floor of room D ranges from 4 to 17 kg as compared to the 1.5 to 2 kg for the two subhorizontal holes in room L4 (Finley et al., 1992). In accord with the results of Finley et al. (1992), from 5 to 15 grams/day of brine were collected from the eighteen BSEP holes near the repository horizon (Deal and Case, 1987).

The five equally-spaced boreholes in the Q access drift were designed to test stratigraphic units immediately below the waste facility horizon, especially MB 139 (Figure 5-11, lower right columnar section). Inflow rates from these boreholes have been both the greatest and the most variable of the three areas sampled, with an average of 14 kg/hole/yr. However, borehole QPB02, which is located in center of the drift, has produced more than half (63.9 kg) of the 113.4 kg of cumulative brine inflow (Figure 5-12) in two years and QPB05 has produced nearly one-third. A fracture was identified in QPB02 and a salt encrustation—or clay-covered perturbation—was found in QPB05; excavation-induced fracturing in MB 139 may explain these variable results and brine influx histories (Finley et al., 1992, Figure 12; Table 2).

Increasing, decreasing, and fairly steady inflow rates have all been observed in 15 of the 17 boreholes; all three types of behavior frequently occur in the same borehole. Most of the boreholes showed a high initial mass flux followed by a monotonic decrease in flux with time. Eleven of the 15 brine-producing boreholes have shown increasing flow rates during the last year (Finley et al., 1992) a response also noted for BSEP holes (Deal et al., 1989). Steady or increasing inflow rates are most probably the result of ongoing fracture development because, in a confined reservoir, flow rates would decrease with time, as is observed in the early history of nine of the boreholes.

Nowak et al. (1988) present a WIPP brine flow model that assumes transient Darcy flow in a porous medium and predicts brine inflow rates for comparison with those observed in the BSEP program (Deal and Case, 1987). Combined with conservative values for the fluid diffusivity, viscosity, and the borehole radius, the apparent permeability (k) at hydrostatic fluid pressure for long times was estimated to be 3.5×10^{-21} m^2. This estimate falls within the range 10^{-20} to 10^{-21} m^2, a range then believed to be representative of far-field permeabilities on the basis of in situ tests (Petersen, 1987).

Expected brine accumulations, using this permeability range and pore pressures from hydrostatic to lithostatic, were calculated for a WIPP reference disposal room (4 m x 10 m x 91 m; Total Surface Area = 2548 m^2; Volume = 3645 m^3) by means of two-dimensional numerical analyses. For a room in a panel, expected accumulations after a 100-year post-closure period range from 4 m^3

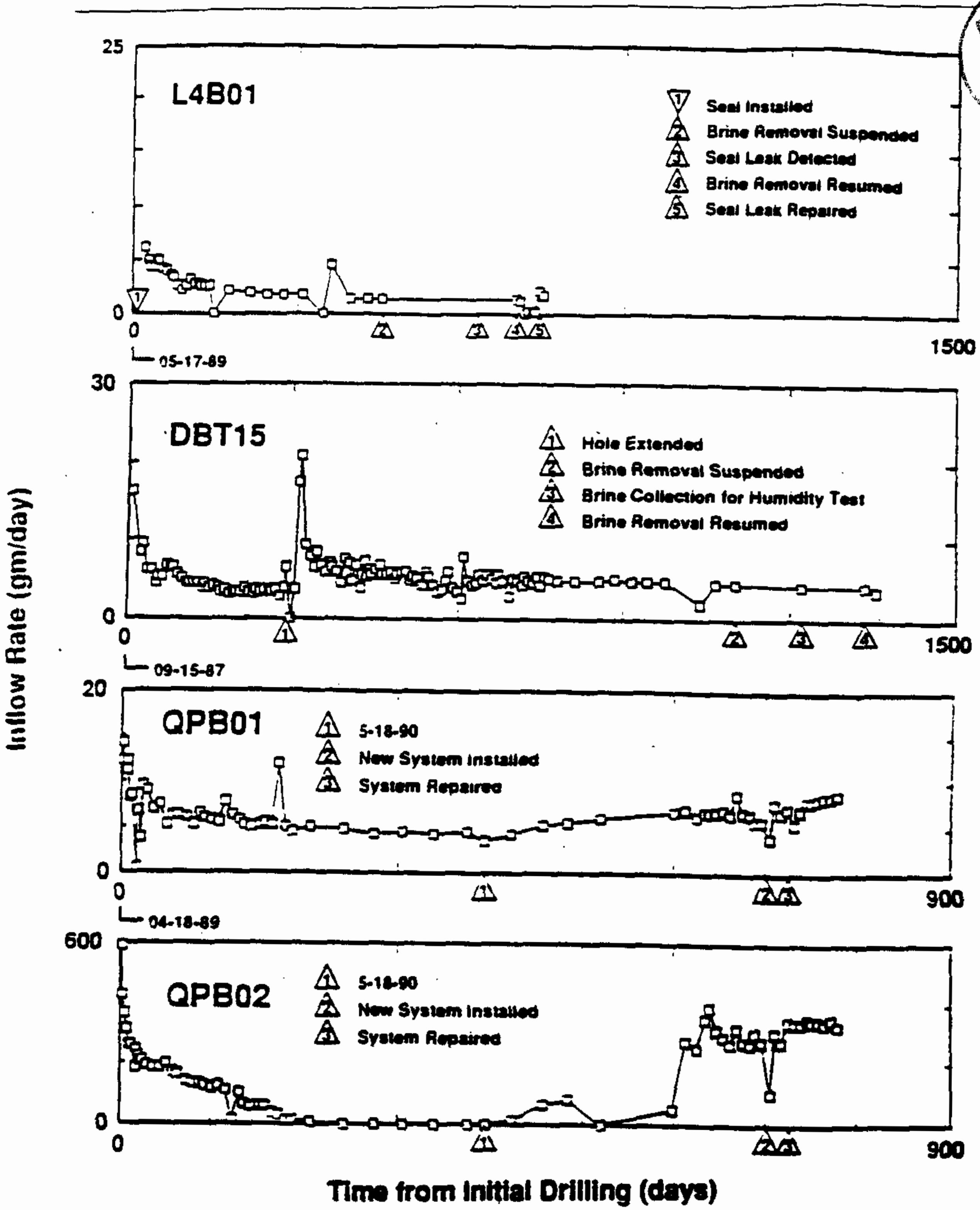


Figure 5-12. Brine Inflow Rates From Boreholes Whose Locations Relative to Repository Stratigraphy are Shown in Figure 5-2 (Finley et al., 1991).

for hydrostatic fluid pressure, P_0 = 6 MPa and k = 10^{-21} m^2 to 43 m^3 for lithostatic fluid pressure, P_l = 15 MPa and k = 10^{-20} m^2 (**Figure 5-13**). The increase in fluid pressure at constant permeability increases cumulative inflow by a factor of two to three whereas a ten-fold increase in permeability at constant fluid pressure increases inflow by a factor of four to five. Nowak et al. (1988) regard 43 m^3 (1.2% of the room volume) as an upper bound on brine flow into disposal rooms. Lappin et al. (1989, p. 3-14) note also that the estimates of Nowak et al. may be inherently high because of flow model assumptions and system characterization uncertainties. Bredehoeft (1988) obtained similar results for this permeability range in his numerical analysis of brine inflow.

5.3 GAS GENERATION

Preliminary analyses of post-closure evolution of disposal rooms indicate that significant quantities of gas may be generated by anoxic corrosion of steel containers and iron-based alloys in the waste and by microbial degradation of cellulosics (Lappin et al., 1989). Brine quantity and chemistry are important in considerations both of radionuclide solubility and of gas generation rate (Davies et al., 1992). Gas-generation rates are reduced if the environment is humid rather than inundated and are reduced still further if conditions are oxidizing (Brush, 1992). Under aerobic conditions, gas is not generated by metal corrosion, and microbial activity produces only CO_2 and H_2O (DOE/WPIO, 1992, p. 2-21). However, for the long-term time frame, following creep closure of the repository, anaerobic conditions should prevail, and sufficient gas may be produced to become a factor in repository behavior.

Pores in the waste, through time, will be filled with brine and/or gas generated by corrosion and biodegradation. After interaction with room contents, brine chemistry and availability are expected to affect gas generation rates during anoxic corrosion by defining the thermodynamic activity of water in the liquid and vapor states. The absolute humidity of the repository atmosphere in equilibrium with Salado brines, as a function of variations in chemistry and temperature, may range from 18 to 27 g/m^3 (DOE/WPIO, 1992). On the basis of preliminary experiments (Brush, 1991), inundated gas generation rates from anoxic corrosion are estimated at 1 mole/drum/year, about the same as those due to microbial activity; radiolysis of brine is expected to produce only 1 x 10^{-4} moles/drum/year. Inasmuch as 6,804 drums are placed in each waste disposal room, the annual amount ~~volume~~ of gas generated ~~at atmospheric pressure~~ is estimated to be about 1.4 x 10^4 moles. If conditions are humid rather than inundated, the rates and annual gas production volumes will be lower by a factor of approximately ten (Brush, 1991). The total gas production potential per drum is about 1,600 moles (1,050 - anoxic corrosion, 550 - microbial activity) for a total (equivalent disposal room) volume of 1.1 x 10^7 moles (Beraun and Davies, 1991). Depending on room environmental conditions and the microstructural state of the surrounding rock, this total production potential could be realized sometime between a few hundred and greater than 10,000 years.

The gas generated must be stored in the available void space in the waste, the backfill and the air gap within each disposal room. This storage volume decreases with time during creep closure until the pore pressure exceeds the hydrostatic pressure. Initially, the air gap volume per room is 649 m^3 and the waste volume is 1,663 m^3 (Beraun and Davies, 1991). Variations in porosity of the

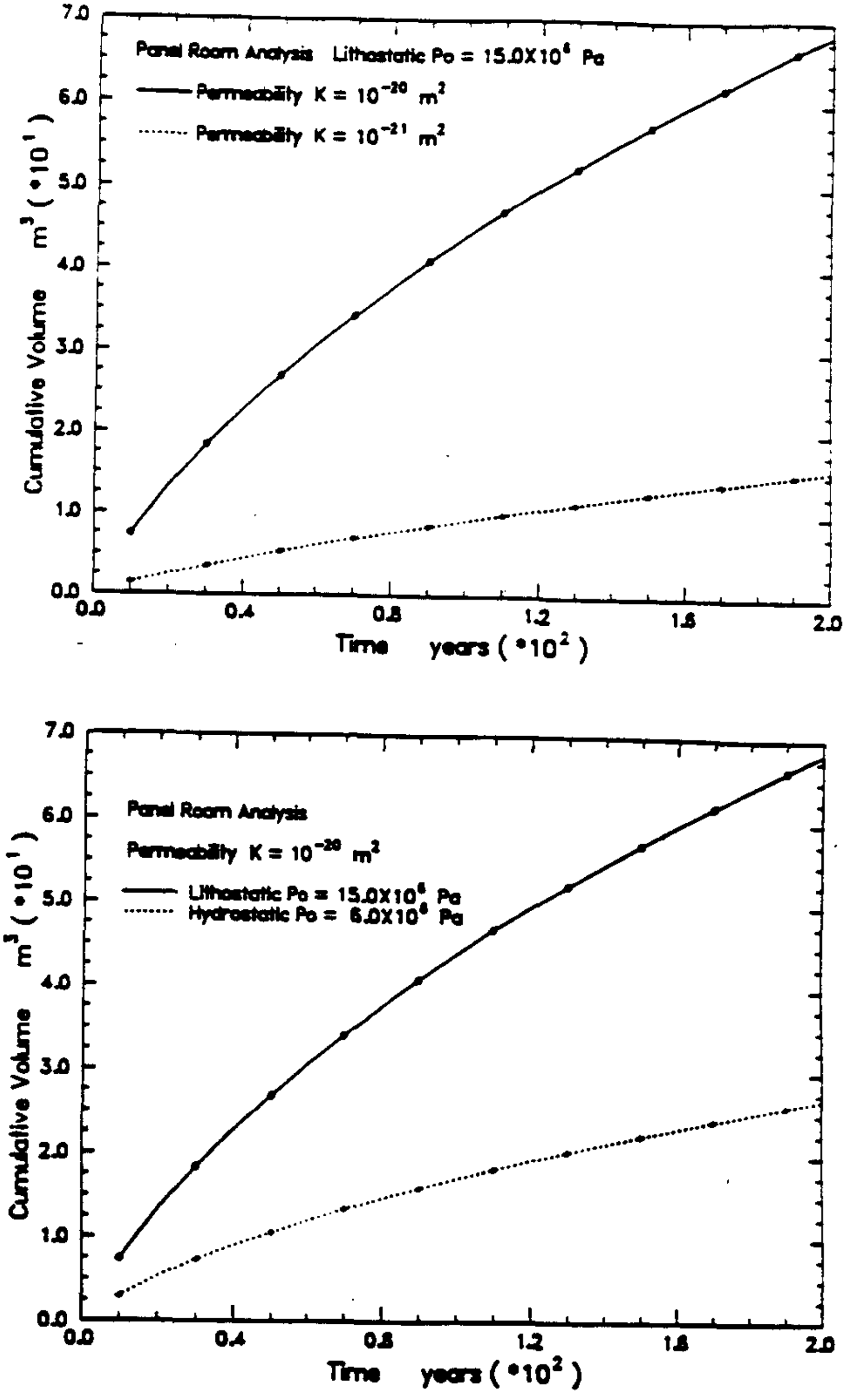


Figure 5-13. Cumulative Brine Volumes in a Disposal Room as a Function of Time for Salado Formation Permeabilities of 10^{-20} and 10^{-21} m^2 and Pore Pressures of 6 and 15 MPa. The values were calculated from a brine transport model using BSEP data and assuming Darcy transient flow in a porous medium (Nowak et al., 1988).

compacting waste as a function of pressure are shown in **Figure 5-14** (Butcher, 1990; 1992; Davies et al., 1991; Beraun and Davies, 1991). Properties of the crushed salt backfill are reasonably well-established by means of laboratory-scale compaction experiments (e.g. Holcomb and Shields, 1987; Holcomb and Zeuch, 1990; Pfeiffle and Senseny, 1985; Case et al., 1987): The backfill occupies a volume of 1,328 m^3 and has an initial porosity of about 0.4 (Beraun and Davies, 1991). Thus, the initial void space will be 649 m^3 (gap) plus 1,300 m^3 (waste) plus 530 m^3 (backfill) or 2,479 m^3. The "final" void volume available following closure will be about 425 m^3 (26% of 1,663; Davies et al., 1991) in the waste, since the air gap disappears and void space in the backfill will be isolated as the crushed salt becomes relatively impermeable, (Lappin et al., 1989) (Italcomb and Shield, 1987). At the maximum gas generation rate (1.4 x 10^4 moles/yr), assuming no leakage, 50 m^3 of brine, and ideal gas behavior, 375 m^3 of void space would be occupied at 27°C (300 K) and 15 MPa pressure (lithostatic) in 160 years. Lappin et al. (1989) estimate a minimum final void volume of about 109 m^3 (0.03 of initial volume) so that only about sixty years of maximum gas generation are required to produce a gas pore pressure equal to the lithostatic pressure.

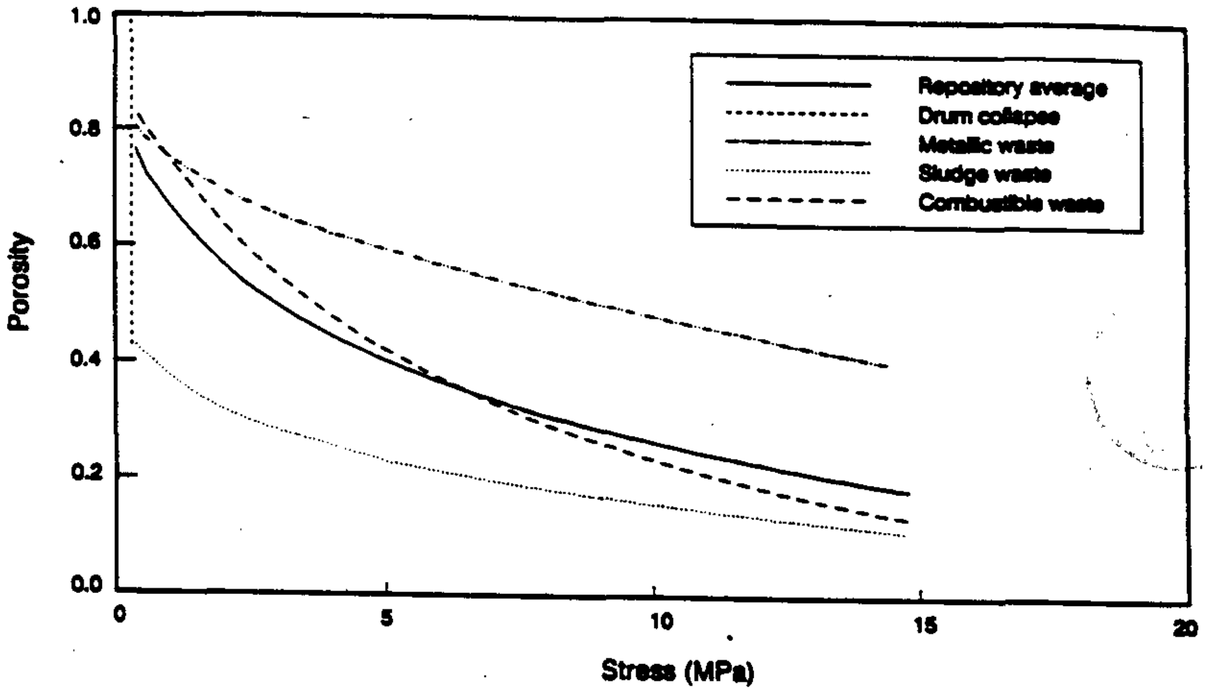


Figure 5-14. Variation in Porosity (f) of Waste as a Function of Pressure (Davies et al., 1991).

5.4 GAS FLOW

Maximum gas pressures calculated above assume, among other simplifications, that gas is entirely contained within the room. If the surrounding rock is fully saturated with brine, as is assumed for Salado members in the far-field, then the relative permeability to gas is zero. In order for gas to flow outward, it must establish interconnected pathways after exceeding resistive capillary forces (threshold pressure) and existing brine pore pressure in the rock (Davies, 1991). Davies' threshold pressure estimates of Salado Formation members are (1) for relatively pure, undeformed halite, 25 to greater than 50 MPa; (2) for impure halite, mildly deformed halite and some interbeds, 5 to 25 MPa; and (3) for interbed units containing pre-existing, partially healed fractures, 0.5 to 2 MPa (**Figure 5-15**). Therefore, if the far-field pore pressure in halite is 9.5 MPa and the gas pressure within the reservoir builds to lithostatic (15 MPa), then lithologic units beyond the depressurized zone with a threshold pressure of less than 5.5 MPa may permit gas penetration.

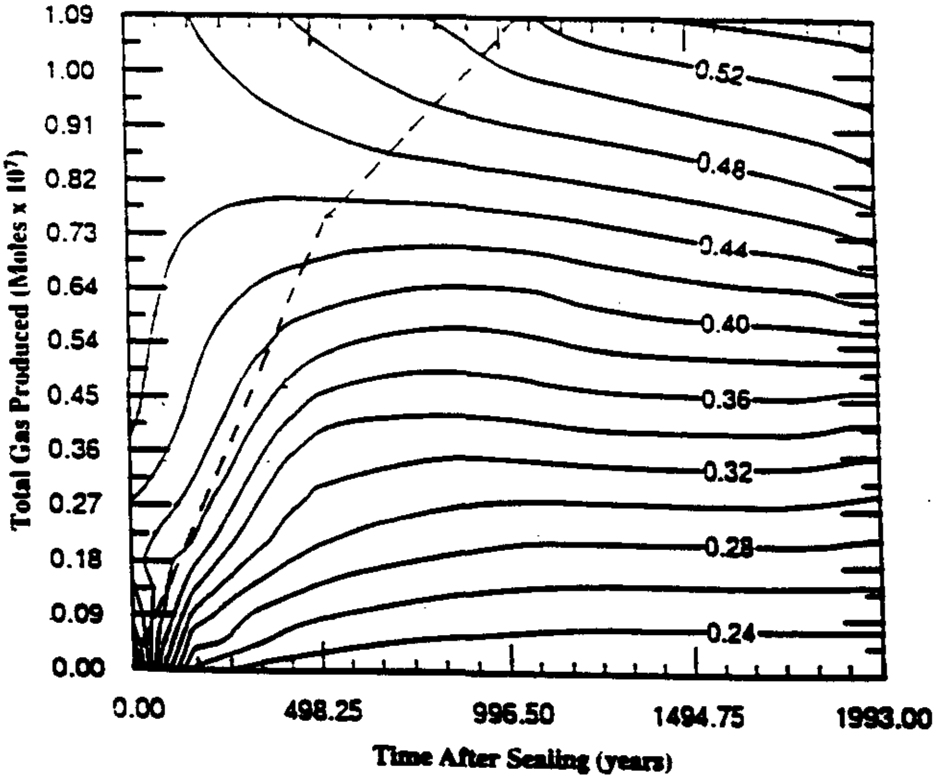


Figure 5-15. Relative Permeabilities and Threshold Pressures of Salado Formation Units in the Far-Field and Near-Field (Davies et al., 1991)

Only nonhalite interbeds and, perhaps, some impure halite members are likely to permit gas outflow under these conditions. For the near-field, several processes involved in creating the disturbed and depressurized regions will interact to provide a zone of low threshold and pore pressure. This near-field zone, which may have significant gas storage potential, is likely to provide partially desaturated pathways for gas to flow to nonhalite interbeds that have relatively high permeabilities and low threshold pressures (Davies, 1991). Possible hydraulic fracturing of MB 139 would also serve to relieve gas pressure and provide gas storage volume.

5.5 COUPLED EFFECTS OF CLOSURE AND FLUID FLOW ON REPOSITORY BEHAVIOR

On the basis of the foregoing summary of processes expected to occur in the repository following closure, it is clear that the overall behavior will depend primarily on strongly coupled rates of creep closure, brine inflow, and gas generation. Davies et al. (1991; 1992) give examples of possible effects of coupled brine flow and gas generation on disposal room pressures and volumes through time. Their two-dimensional model assumes an isolated room in salt (k = 10^{-20} m^2) in hydraulic communication with higher-permeability (k = 10^{-19} m^2) interbeds, an initial pore pressure of 11 MPa and an intermediate closure state with 1,000 m^3 void volume. Brine inflow rate (initially at 0.48 m^3/year) is reduced by increasing gas pressure, so that further gas generation takes place under partially humid (.003 mole/drum/year) rather than fully inundated (3 moles/drum/year) conditions. Effects of variable gas generation rates on room pressure to 1,400 years are shown in **Figure 5-16**. In this model, gas pressure does not exceed lithostatic pressure (15 MPa) in the first 1,000 years.

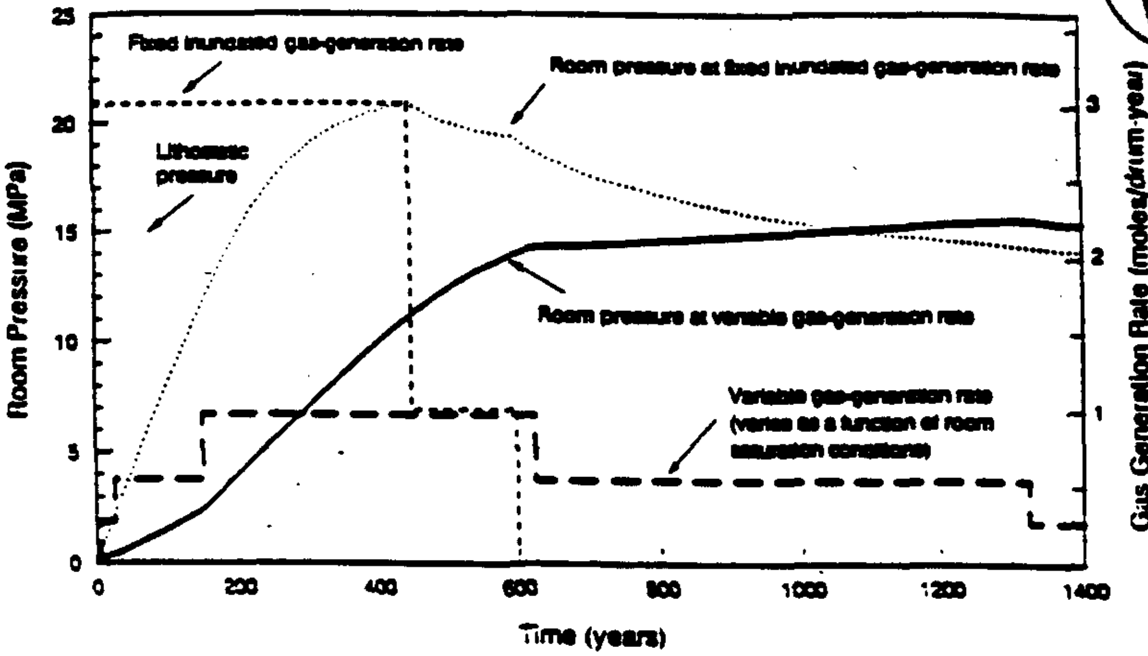


Figure 5-16. **Room Pressure Calculated for Inundated (dotted curve) and Variable (solid curve) Gas-Generation Rates (Davies et al., 1992; Figure 10).**

Waste and backfill consolidation during creep closure of the rooms causes a significant reduction in void volume available to store waste-generated gas. Therefore, gas pressure rises in the room, which, in turn, resists further consolidation and closure. Modeling salt flow as that of a highly viscous fluid, Davies et al. (1992) coupled brine and gas flow between a disposal room and surrounding rocks in a three-phase (salt, brine, gas), fully-coupled system. The resulting room pressure as a function of time is shown by the solid curve in **Figure 5-17**, in comparison with results obtained for two-phase (gas and brine) flow in a room of fixed geometry. Results from simulations shown all assume a gas generation rate of three moles/drum/year and do not allow for coupling with brine availability. As seen in Figure 5-16, pressure buildup will occur at a much lower rate for variable gas generation rates.

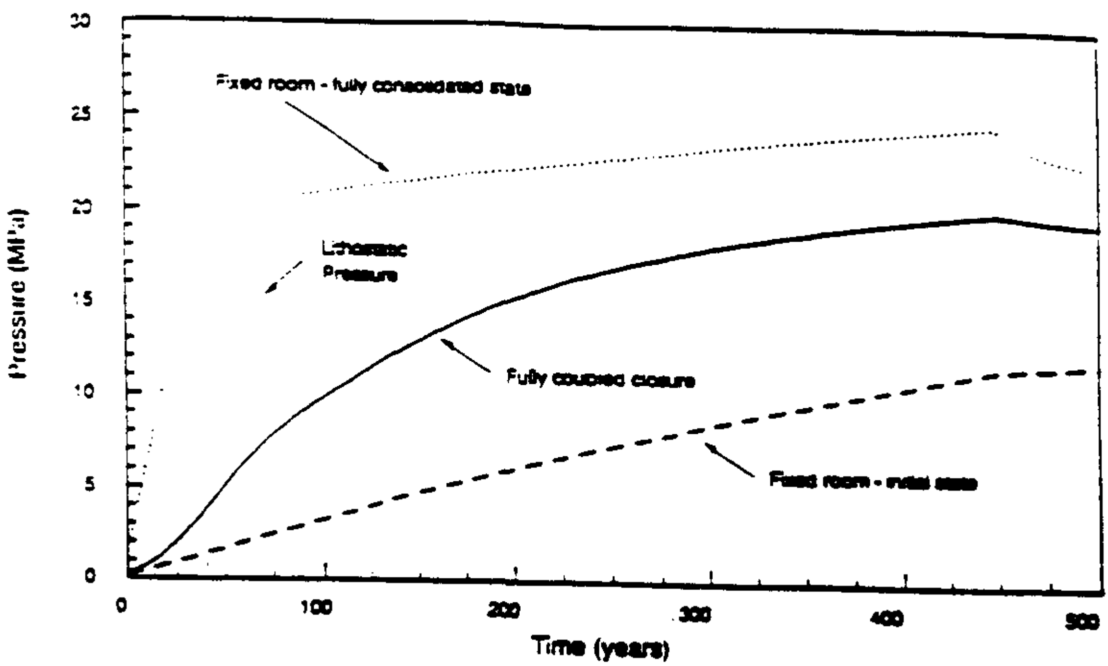


Figure 5-17. **Room Pressure as a Function of Time for a Fully-Coupled (solid curve), Three-Phase System (Davies et al., 1993; Figure 16).**

The microstructural state of salt, which comprises greater than 90% of the DRZ around waste disposal rooms, is also critical to repository response and must be accounted for in the coupled approximations. The volume occupied by the DRZ, approximated by assuming that it extends 3 meters into the salt, is from three to four times that of the disposal room, in the initial and fully-closed state, respectively, and hence its time-dependent physical properties are of paramount importance. If creep closure to the fully compacted state takes place within 100 years, unimpeded by brine inflow and gas pressure (Lappin et al., 1989; Marietta et al., 1989; PA, 1992; Davies et al., 1992), then the DRZ would self-heal to nearly intrinsic far-field permeability. This possibly healed condition is not accounted for in current PA calculations, Beauheim (1993). Gas generation during this period is estimated to be 1.4 x 10^5 moles per room from both microbial decay and anoxic corrosion in a humid environment (0.2 moles/drum/yr) since only about 50 m^3 of brine is available for the process. Assuming that no gas leakage occurs, the gas would occupy about 350 m^3 pore space in fully compacted waste, giving rise to a gas pressure of 1.0 MPa. Under these conditions, ideally the DRZ would self-seal, providing an impervious shield greater than 1 m (3.3 ft) thick around the waste whose only pathway to the accessible environment is migration along thin clay interbeds and gas venting along rock bolts in the roof to anhydrite layer B. Swift (Beauheim et al., 1993) reports that mining in some portions of the repository involves excavation to MB 139 followed by backfilling to the specified grade. He suggests that it is more realistic to assume that MB 139 will always be in contact with backfill and waste.

6.0 ENGINEERED BARRIERS

This section discusses issues related to the engineered barrier system for a WIPP repository. The discussion is based on a review of a large number of WIPP documents covering a range of topics that are directly or indirectly related to engineered barriers. In general, the review attempted to address the following questions:

- What quantitative and qualitative analyses have been performed relevant to the engineered barriers for the repository?
- What laboratory and field experiments have been performed?
- What is the expert opinion concerning engineered barriers for a salt repository?
- How are the potential pathways and seals being considered in the PA analysis?
- What data are available concerning geochemical compatibility?
- What criteria have been established to determine the requirements of the barrier system?
- What are the remaining issues related to engineered barriers and how are they (or are they not) being addressed?

The performance of engineered barriers at WIPP will depend on several related and often coupled mechanisms and processes. Seal performance will be determined by the creep closure of the underground openings, consolidation of crushed salt, the volume of brine inflow during consolidation, gas-generation rates in the disposal rooms, the extent and healing of the disturbed zone, the permeability of interbeds, and the ability to seal fracture zones. The following discussion touches on many of these aspects. More complete coverage of some of these topics is contained in other sections of this report and the reader is encouraged to refer to them for a more comprehensive treatment.

Subsection 6.1 provides background information concerning the purpose of engineered barriers, applicable parts of the regulatory standards, and a description of the current design concepts. This is followed by a review of the analyses (Subsection 6.2) and tests (Subsection 6.3) that have been performed to assess the viability and performance of repository seals. A summary of the issues associated with the sealing of a repository and planned tests and analyses to address them is presented in Subsection 6.4.

6.1 BACKGROUND

Engineered barriers are crucial to the successful isolation of TRU and hazardous waste from the accessible environment. Engineered barriers include repository design features and engineered components that contribute to the capability of the repository system to meet the radionuclide and hazardous materials release limits set by applicable regulations. The fundamental role of the engineered barriers is to act in conjunction with the natural system to minimize the release of radioactive and hazardous waste from the WIPP repository. Engineered barriers may include

- drift seals,
- shaft seals,
- borehole plugs,

- disturbed rock zone (DRZ) seals,
- interbed seals,
- panel seals,
- backfill,
- waste form, and
- waste packages.

This discussion and those that follow are restricted to sealing aspects of the engineered barrier system and do not directly address waste form and waste packaging components. The review assumes that the current concept for waste form and waste packaging will be employed at WIPP. Obviously, the requirements for the engineered barrier system, particularly the sealing components, would change if alternative waste forms and waste packages were employed, and the importance of performance issues may shift. For example, the volume and rate of gas generated in the disposal panels from corrosion and microbial processes depends on the containers (currently steel) and waste form (unprocessed waste including large quantities of cellulosic materials). If gas generation was no longer a concern, the performance requirements of the sealing components would likely be different.

The regulatory framework for WIPP requires assessment of cumulative release of radionuclides to the accessible environment under standards promulgated by the US Environmental Protection Agency (EPA) in 40 CFR 191 and assessment of migration of hazardous chemical constituents under standards set forth in the RCRA. There is only one reference to engineered barriers in 40 CFR 191 other than the definitions in 40 CFR 191.12. Requirement 191.14(d) states that "the disposal systems shall use different types of barriers to isolate the waste from the accessible environment. Both engineered and natural barriers shall be included." Other references to engineered barriers are contained in Appendix B, Guidance for Implementation of Subpart B, 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.

Among the standards set forth in RCRA, the Land Disposal Restrictions (40 CFR 268) regulate disposal of specified non-radioactive hazardous wastes. The standards are applicable to WIPP because the transuranic wastes include nonradioactive components, such as heavy metals, as well as volatile organic compounds (VOCs) and other contaminants covered under 40 CFR 268. The regulations prohibit the disposal of these wastes unless the owner or operator of the facility petitions for a variance and demonstrates that there will be no migration of the hazardous constituents (above health-based levels, EPA, 1992) as long as the waste remains hazardous.

In their response to a DOE no-migration variance petition, the EPA has stated that the DOE must address uncertainties about long-term WIPP performance before the DOE may proceed with full-scale operations. Among the uncertainties identified by EPA were the extent and effects of gas generation, effects of brine inflow into the repository, and the influence of the disturbed zone surrounding the mined repository (US EPA, 1990). Each of these uncertainties will play some role in determining the requirements for and the performance of engineered barriers. Gas from the repository could transport VOCs either horizontally from the repository in the interbeds or vertically up the shafts. The transport pathways and concentration of the VOCs will be determined, in part, by the type and performance of engineered barriers used. Similarly, pressurized brine may transport heavy metals and dissolved VOCs (as well as radionuclides) through the same potential pathways.

The information required to support a demonstration of no-migration in compliance with 268.6(b) includes the results of numerical flow and transport analyses of overall system performance. Additional data from laboratory and field tests will be required to verify that the engineered barrier components of the system will perform as designed.

6.1.1. Current Design Concepts

In the reference design, multicomponent seals will be located in each of the four shafts, in the entrances to the waste disposal panels, and in selected access drifts. The locations of the various seals in the WIPP repository are shown in **Figure 6-1**. The design includes multiple shaft seals and drift seals at strategic locations within the repository. Because the purpose and function of the seals vary with their location, the shaft seals and drift seals will be discussed separately.

The four shafts are the most likely pathways for the transport of mixed waste to the accessible environment under undisturbed conditions (no human intrusion). The strategy for sealing the shafts is to maximize the amount of consolidated, low permeability salt in the shaft between the top of the Salado Formation and the repository level (Stormont, 1988a). The current design for shaft seals includes two types of seals: long-term seals consisting of segments of consolidated crushed salt (**Figure 6-2**); and short-term, composite seals (**Figure 6-3**) intended to prevent brine from contacting the crushed salt seals before it can be consolidated to a density close to intact halite.

Creep closure of the shaft opening is expected to consolidate the crushed salt in the lower portion of the shafts to near-intact (95%) density within 100 years after emplacement (Nowak and Stormont, 1987; Arguello, 1988; Lappin et al., 1989). To facilitate the consolidation phase, composite seals will be located above and below the crushed salt seals to prevent brine from saturating the crushed salt and inhibiting consolidation. Composite seals will be placed at three locations: above the upper salt seal, below the lower shaft seal, and in between the upper and lower salt seals (see **Figure 6-4**). Because the concrete bulkheads in the composite seals straddle the long-term seal intervals, they will also serve as reaction frames to restrict vertical movement of the salt during consolidation.

Fractures in the DRZ surrounding the shafts are expected to heal once the crushed salt reaches 95% density and resists further creep closure and the field stresses return to hydrostatic conditions. The permeability of the DRZ adjacent to the concrete bulkheads in the composite seals is expected to return to near in situ levels shortly after emplacement because they will resist creep closure.

The use of crushed salt as the primary, long-term sealing material for openings in the Salado Formation obviates any concern about seal longevity. The material is, for all practical purposes, identical to the surrounding halite and should have similar chemical and hydrologic properties once the material has consolidated. The concrete bulkheads are expected to degrade with time but remain functional during the near-term when the crushed salt seal is consolidating.

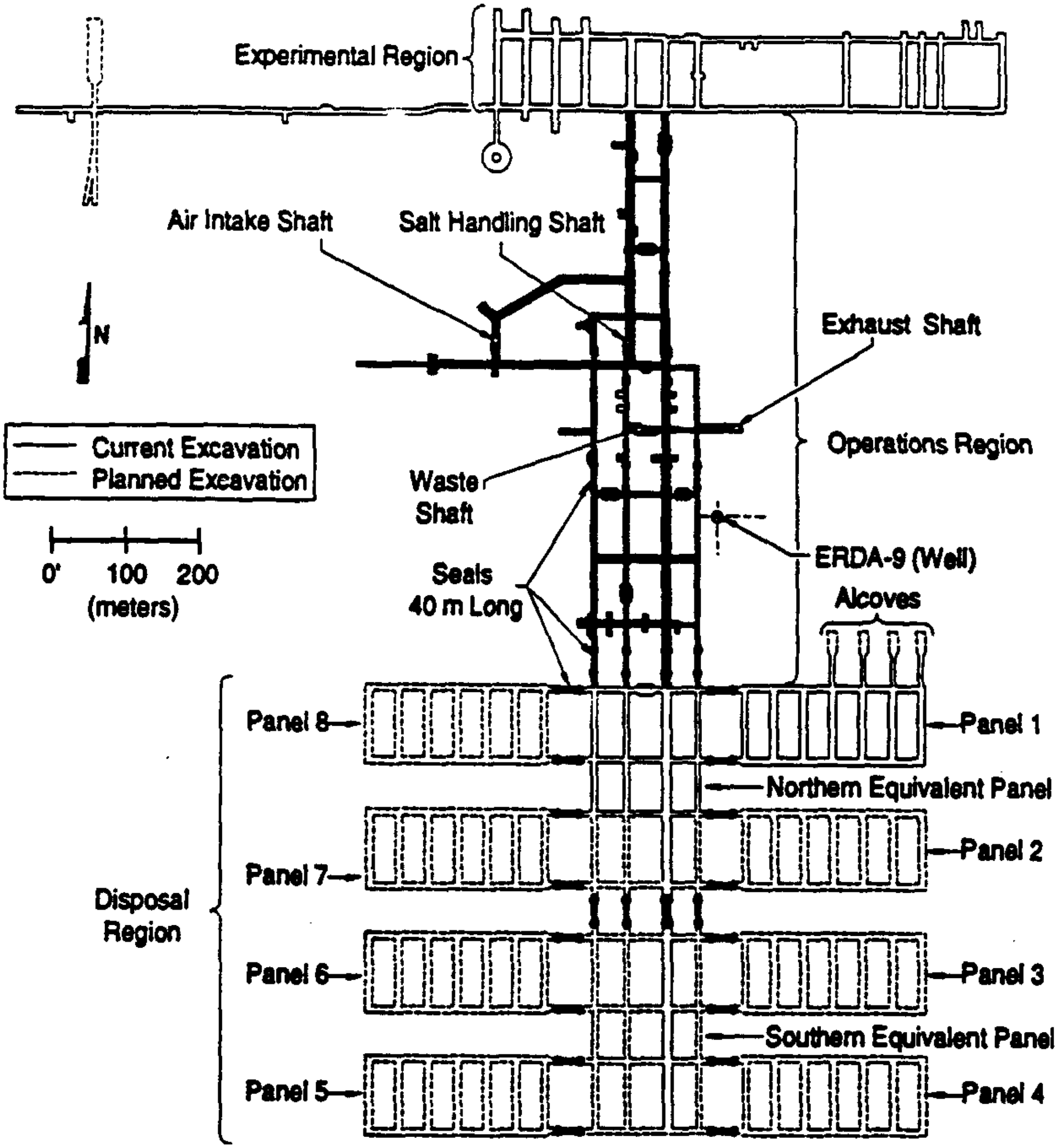


Figure 6-1. Location of Panel Seals

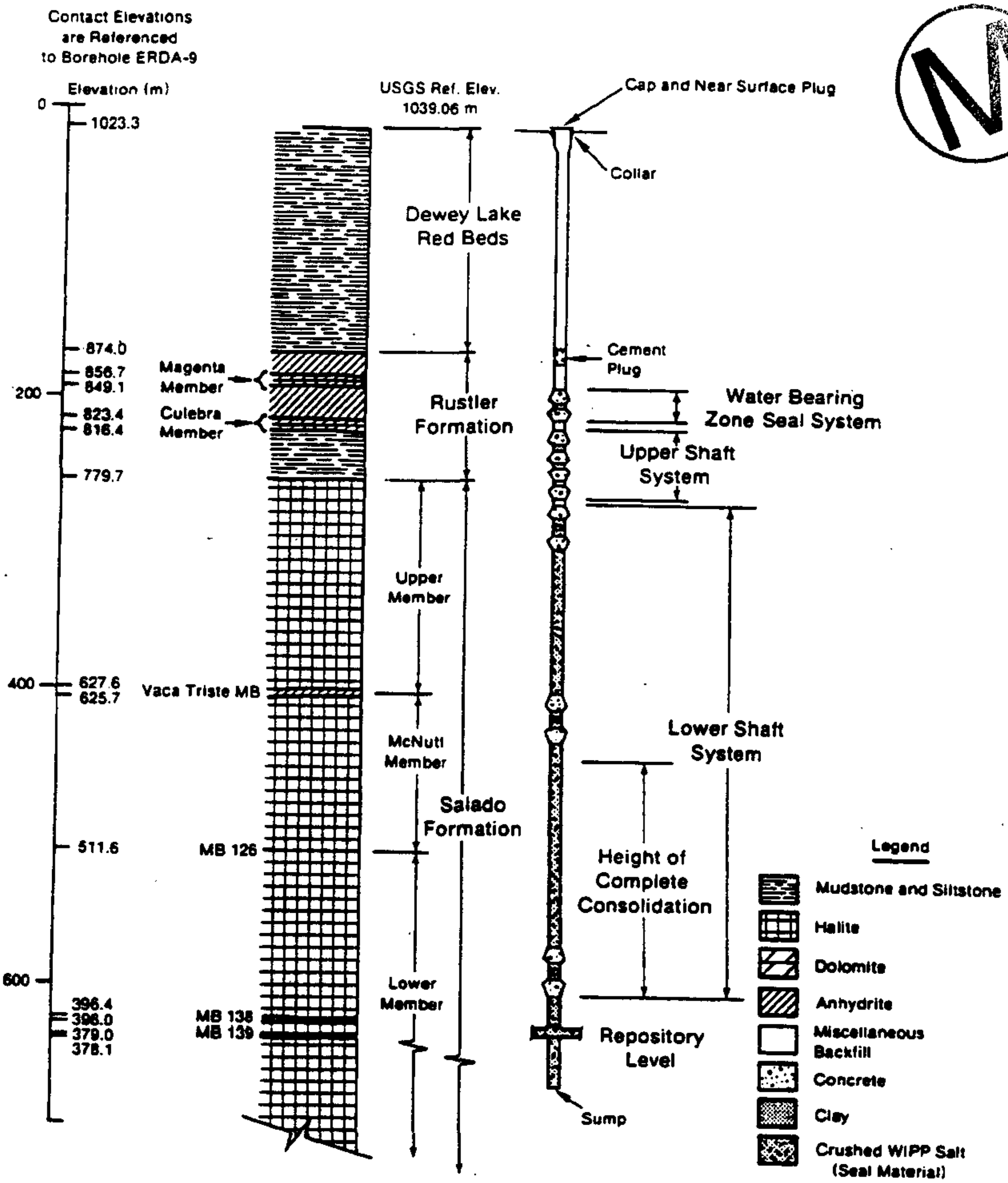


Figure 6-2. **Diagram of Typical Sealed and Backfilled Access Shaft (after Nowak et al., 1990).**

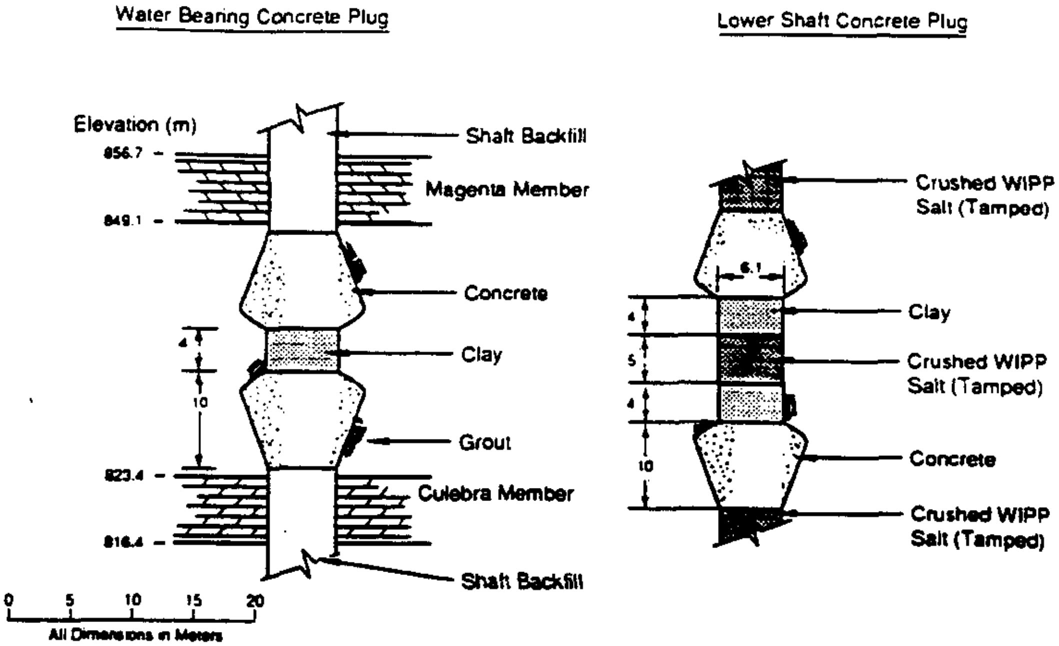


Figure 6-3. **Diagram of Typical Concrete Plugs in Backfilled Shafts Showing Combination of Different Materials Depending on Location Within the Shaft (after Nowak et al., 1990).**

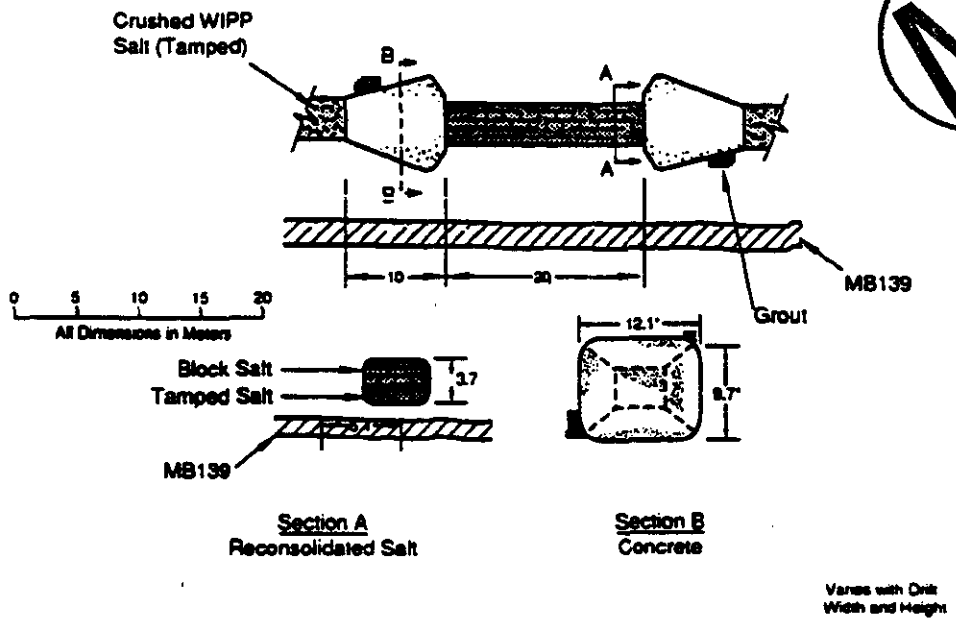


Figure 6-4. **Diagram of Preliminary Design for Concrete and Preconsolidated Crushed Salt Seal for Drifts and Panels (after Nowak et al.). (Vertical dimensions are exaggerated.)**

The upper shaft seal system in the Rustler Formation will comprise of a sequence of seals made up of bentonite clay segments (4 m in length {13 ft}) confined by adjacent concrete bulkheads. The purpose of the seals is to limit groundwater flow from the formation into the lower portions of the shaft during the consolidation phase of the crushed salt seals. The bentonite will be emplaced at an initial density tailored to allow water uptake and swelling pressures that will prevent groundwater flow down the shaft but within the limits imposed by the strength of the host rock and concrete bulkheads. The shaft liners will be removed prior to constructing the seals, to allow direct contact between the bentonite and Rustler Formation. The DRZ surrounding the shafts may be removed or sealed with grout to prevent groundwater from flowing around the plugs and into the underlying crushed salt seals.

The panel and drift seals are designed to inhibit long-term migration of radionuclide-contaminated brine through the drifts to the base of the shafts and isolate the panels during the operational phase of the repository (Sandia National Laboratories, 1992). The seals are similar to the shaft seals and comprise both long-term and short-term seals.

The current design for panel seals is shown in Figure 6-4. The seal consists of 20 m (65 ft) of pre-consolidated crushed salt confined between two 10-m (33 ft) concrete barriers (Nowak, Tillerson, and Torres, 1992). The panel entryway seals are intended to return intervals within the repository to hydraulic properties similar to the intrinsic conditions in the undisturbed host rock salt. In this way, the seals are expected to provide substantial resistance to flow through the repository as well as separating volumes of waste from one another and from the shafts. The concrete bulkheads serve to confine the crushed salt during consolidation and provide resistance to gas flow during this period. The time for consolidation is similar to that for the lower shaft seals, i.e., approximately 100 years after installation.

The DRZ in the salt surrounding the seal locations is expected to heal eventually after the crushed salt reaches 95% fractional density and resists further creep closure of the opening. The disturbed zone around the concrete bulkheads is expected to heal much earlier, due to the back stresses that will be generated. Marker Bed (MB) 139 and the other interbeds adjacent to the repository may need to be sealed above and below each panel and drift seal by grouting, with crushed-salt-based grout, cementitious material, or bitumen. The DRZ and the interbeds represent pathways for bypassing the panel seals.

The performance criteria for the seal components must be defined before the seal design can be finalized. The criteria will be determined, to a large extent, by the results of performance assessments of the WIPP repository system. The preliminary performance assessment analyses of the entire repository system have not included all aspects of the natural and engineered barriers that may influence system performance; therefore, the seal designs and design concepts are preliminary. Stormont (1988a) has identified the following predominant processes which may impact the performance seals and the repository system:

- Closure of the excavations in the Salado Formation and the consolidation of the crushed salt in the long-term seal components;
- Brine inflow into the excavations in the Salado Formation which may inhibit crushed salt consolidation, accelerate corrosion of waste packages, and, if present in discrete pockets, result in pressurized brine;
- Corrosion of the waste package and metallic waste and the generation of gases;

- Water inflow from the Rustler Formation and possible dissolution of salt seals, inhibition of crushed salt consolidation, and creation of pressured brine pockets;
- Creation and long-term behavior of the DRZ around excavations as potential pathways for the transport of contaminants in brines or gases.

These issues are being addressed in a variety of laboratory and field studies, as well as in numerical analyses. The programs are discussed in the following Subsections, and their adequacy to resolve these issues is assessed.

6.2 TESTING ACTIVITIES

The sealing strategy and reference design are supported by numerous laboratory and field tests. These include testing to demonstrate the relatively rapid consolidation of crushed salt under a wide range of pressures, in situ emplacement of crushed salt and bentonite blocks in small-scale seal environments, characterization of the DRZ and interbeds, and in situ testing of prototype grouts and injection technology. The following discussion provides a summary of these tests and their results.

6.2.1 Consolidation of Crushed Salt

When crushed salt is subjected to sufficient confining pressures, it consolidates and eventually achieves porosity and permeability values comparable to intact salt (IT Corporation, 1984). The crushed salt in the shaft, panel, and drift seals will be consolidated as a result of the creep closure of the adjacent host rock which is a function of depth, the properties of the rock salt formation, the size and shape of the excavation, and the resistance presented by the crushed salt.

At a given stress, the consolidation behavior of crushed salt is strongly influenced by the addition of small amounts of water, several percent by weight (Holcomb and Shields, 1987; IT Corporation, 1984). Stormont (1988a) compared the results of a dry consolidation test by Holcomb and Hannum (1982) with those of Holcomb and Shields (1987) in which a small amount of water was added (less than 3% wt), and found that under similar test conditions (stresses) the time required for the dry crushed salt to experience the same strain as the wet material was five to ten orders of magnitude greater. The exact mechanism responsible for this dramatic difference is not understood, although pressure solution is the preferred hypothesis. Because it is desirable for the crushed salt seal components to reach near-intact properties as soon as possible, the reference design includes the addition of small amounts of water to be added to the crushed salt in the shaft, drift, and panel seals (Nowak et al., 1992).

As the crushed salt consolidates, the porosity and permeability will decrease. **Figure-6-5** shows the results of permeability versus density tests performed by Holcomb and Shields (1987) and IT Corp (1987). In general, the permeability of the crushed salt drops rapidly between fractional densities of 85% and 95% (fractional density is defined as the percentage of the intact salt density). At 95% fractional density, the permeability is expected to be between 3×10^{-20} and 3×10^{-21} m^2 (Nowak and Stormont, 1987) compared to a permeability range of 10^{-19} to 10^{-24} m^2 for intact, undisturbed halite in the Salado Formation (Sandia National Laboratories, 1992c). Therefore, if the crushed salt portions of the shaft, drift and panel seals are consolidated to 95% relative density, the excavation will be returned to its undisturbed state. This assumes the DRZ surrounding the excavations also returns to intrinsic conditions. Interactions between the consolidation of the crushed salt and the creep closure of the excavations and the expected time for consolidation to occur is discussed in Subsection 6.3.

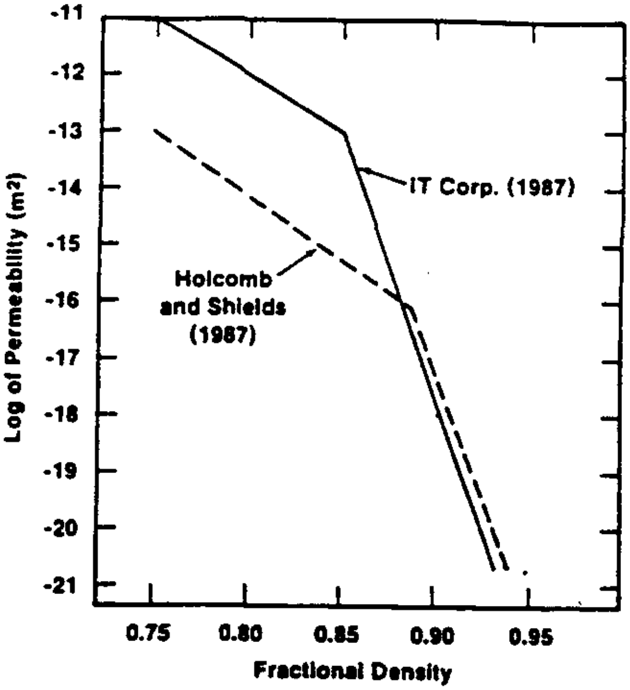


Figure 6-5. **Permeability Versus Fractional Density for Two Consolidation Tests Using Wetted Crushed Salt (Stormont, 1988)**

6.2.2 Other Seal Materials

In addition to crushed salt or quarried blocks of salt, there are a number of other seal materials being considered for use in the WIPP facility: bentonite clay, cementitious materials, and asphalt (Stormont, 1988a). Sandia National Laboratories has performed a series of in situ experiments designed to evaluate the performance of the various candidate seal materials. The tests were performed in vertical and horizontal boreholes ranging in size from 15 cm to 0.9 m (6 in to 3 ft). Test Series A and B experiments evaluated the performance of salt-based concrete in vertical and horizontal boreholes, while Test Series C evaluated salt block and salt/bentonite block-type barriers.

Bentonite has been used for creating fluid barriers in numerous civil and mining applications such as dams, liners for municipal and hazardous landfills, and groundwater control in mines. Bentonite is also an important component in the engineered barrier system for proposed nuclear waste repositories in crystalline rock (Pusch and Borgesson, 1989). A principal component of bentonite is montmorillonite, which swells when hydrated, resulting in good contact between the emplaced material and the surrounding rock. As mentioned in Subsection 6.1, bentonite plugs are being considered as part of the sealing system for the shafts to prevent groundwater from entering the shaft and contacting the crushed salt portion of the system. In the Rustler Formation, the bentonite-based seals will be used to reestablish the natural low permeability of certain portions of the formation (Stormont, 1988a). Within the Salado, bentonite-based seals are planned 15 m (49 ft) into the formation, at an interbed layer around 500 m (1,640 ft) depth, and at the base of the shafts to protect the crushed salt portion of the shaft seal during consolidation.

Test Series C of the Small-Scale Seal Performance Tests included the investigation of salt/bentonite as sealing material. Ninety-two cm-long test seals were constructed in four boreholes. 92 cm in diameter, using a 50/50 mixture of crushed salt and bentonite. The seals were exposed to brine and allowed to hydrate, eventually swelling and effectively sealing the boreholes to further brine movement (Stormont and Howard, 1987). After the seals were emplaced, permeability tests were performed by pressurizing the borehole interval beneath the seal. The permeability of the seal was approximately 1×10^{-21} m^2.

Concrete is often used as a seal and shaft or tunnel liner material in underground excavations due to its availability, relatively low cost, and favorable properties. However, there are few data concerning the performance of concrete seals over time frames or situations relevant to the proposed applications at WIPP (Stormont, 1988a). Available historical evidence suggests that leakage of concrete seals tends to occur at the rock interface or the disturbed zone in the surrounding rock and not within the concrete seal itself. This is not likely to be the case at the repository depth at WIPP, due to creep closure and fracture healing properties in salt.

A salt-saturated expansive concrete developed by Wakeley and Walley (1986) was used to assess the performance of concrete seals in salt in Test Series A and B of the Small Scale Seal Performance Test. The concrete has a unconfined compressive strength of 48.3 MPa and a permeability of 0.8×10^{-18} m^2. Results from the tests have been very favorable (Stormont, 1988a). The seal permeability calculated from gas and brine flow tests was around 1×10^{-18} m^2 (Peterson, Lagus and Lie, 1987), suggesting that the salt/concrete interface was tight and would be capable of limiting brine movement through or around the seal. A potential problem for the concrete seals is mechanical failure and loss of seal performance due to the high stress (compressive and tensile) that may develop as a result of creep closure in the salt. Predicted stress levels are discussed in Subsection 6.3. The strength of the concrete could be increased by adding fiber reinforcement or chemical additives, but these would have to be compatible with the local environment. There is significant uncertainty concerning the longevity of concrete in salt. Concrete shaft liners in nearby potash mines have deteriorated from sulfate attack (Stormont, 1988a) over a twenty-year period. However, the relatively large size of the concrete bulkheads in the shaft and panel seals (10 m (33 ft)) and the tight interface between the concrete and the salt host rock make it unlikely that significant portions of the concrete plugs would degrade prior to consolidation of the crushed salt portions of the seal system.

6.2.3 Disturbed Rock Zone

The performance of the shaft, drift, and panel seals will depend not only on the properties of the seal material (e.g., consolidated crushed salt) but also on the hydraulic properties of the surrounding rock mass and seal/rock interface. The construction of underground openings causes fracturing in the surrounding rock mass due to the redistribution of stress in the immediate vicinity of the excavation. The fractures could provide a pathway for fluid flow around the seals and compromise the performance of the repository. At the repository level at WIPP, the DRZ could extend into existing fractures (pre-excavation) in the relatively brittle anhydrite of Marker Bed 139 and other interbeds (Davies, 1991).

Excavation-related fractures have been documented by visual observation, in drill holes from excavations, by geophysical measurements, and by gas injection (Borns and Stormont, 1988). This fracturing includes vertical separations along nonhalite interbeds in the floor and back, curved fractures in the floor and back that crosscut a variety of stratigraphic units, and vertical fractures associated with spalling within the ribs. Gas permeability measurements by Stormont, Peterson, and Lagus (1987) in the first panel entries provide some insight into how the disturbed zone develops. Initial measurements were performed approximately one month after the drifts were excavated. The span of the drifts varied between 3.9 (13 ft) and 6.0 m (20 ft) which provided preliminary information on whether the extent of the disturbed zone depended on the size of the opening.

The results are summarized in Figures 6-6 to 6-8. **Figure 6-6** shows the flow rate in the halite rock as a function of distance from the excavation. In general, the region within 1 m (3.3 ft) of the excavation has much higher permeability than the undisturbed halite, with the flow rates varying by several orders of magnitude. Beyond 1 m (3.3 ft) the flow rates are consistently low. Relatively high flow rates were observed in the interbeds (MB 139 and Seam B) within 2 m (6.5 ft) of the excavation (**Figure 6-7**). The disturbance was greatest near the center of the drift. As shown in **Figure 6-8**, the degree of disturbance appears to be related to the span of the excavation with increasing flow rates in the wider drifts.

Additional gas flow measurements were made in a four-year-old drift similar to the panel entry drift (Borns and Stormont, 1988). Tests were performed in an array of boreholes drilled radially to a depth of 10 m (33 ft). The results are illustrated in **Figure 6-9** that contains contours of gas flow rate around the drift. The measurements indicate increased flow rates in the immediate vicinity of the excavation decreasing radially outward. The effect is present in the back and floor as well as in the pillars. Peterson (1987) conducted gas tracer studies in the same drift by injecting diluted tracer gas into packed-off regions of a borehole and monitoring its arrival in the surrounding boreholes. The gas was injected into two vertical boreholes (one in the back and one in the invert) and one horizontal (in the rib) borehole within 1 m (3.3 ft) of the excavation. The tests in the vertical boreholes indicated that the flow path direction for the gas was predominantly vertical, while the horizontal test indicated that the predominant flow path direction was parallel to the drift face. The effective aperture of the flow paths calculated from the tests was small (approximately 1×10^{-6} m). Stormont et al. (1987) performed additional tracer experiments to study the fracture continuity and effective aperture of the flow paths in MB 139. Tracer gas arrival times and locations suggest that the aperture of the flow path increases with increasing excavation spans. The calculated aperture was approximately one order of magnitude greater at the intersection of two drifts than under a single drift (0.04 cm versus 0.002 cm). The predominant flow direction was vertical from MB 139 to the excavation, consistent with the observations made by Peterson (1987).

Borns and Stormont (1988) visually examined the fractures in the disturbed zone, using boreholes in the rock surrounding the excavation. Fractures with apertures greater than 2 mm were common. Their observations are summarized in **Figure 6-10**, which represents an idealized cross-section of a storage room. The localized fracturing of the rock mass is elliptical and predominantly concave towards the opening. The fractures in the invert and back tend to crosscut the stratigraphy (interbeds), which is consistent with the results of the tracer experiments. Similarly, the

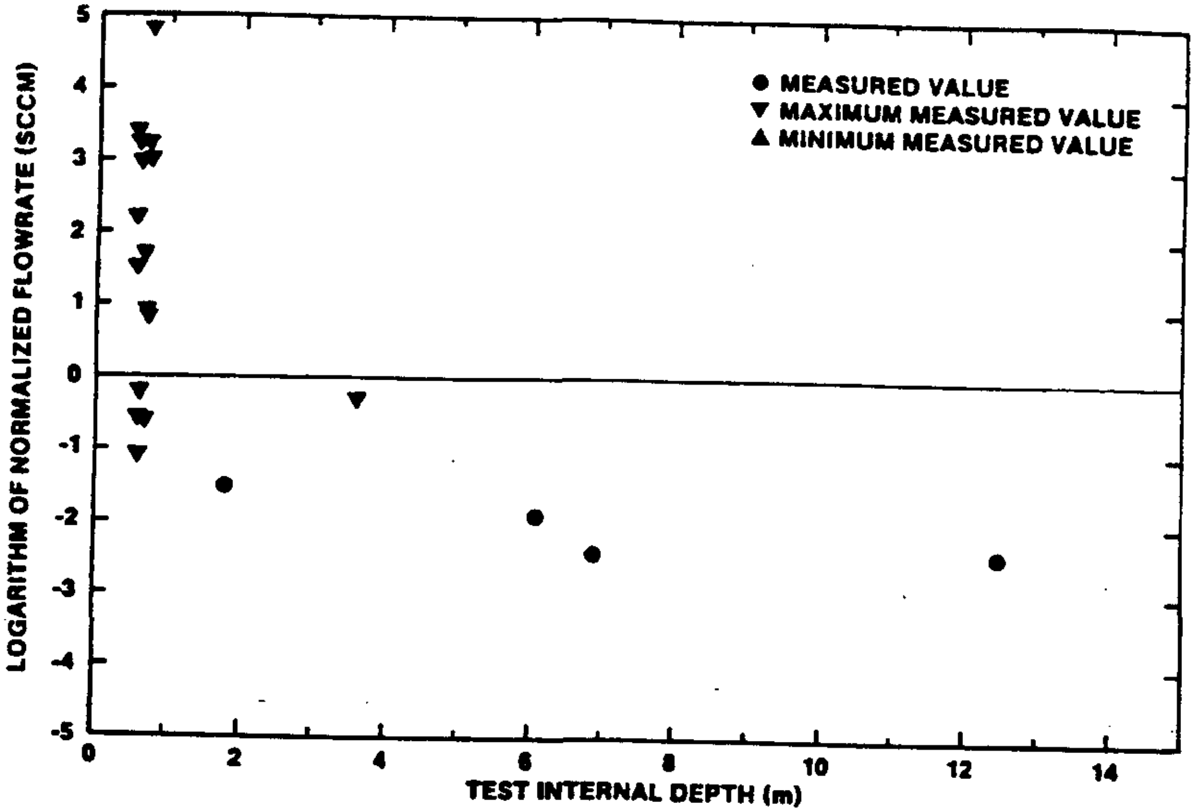


Figure 6-6. Gas Flow Rates in Halite Test Interval (Borns and Stormont, 1988).

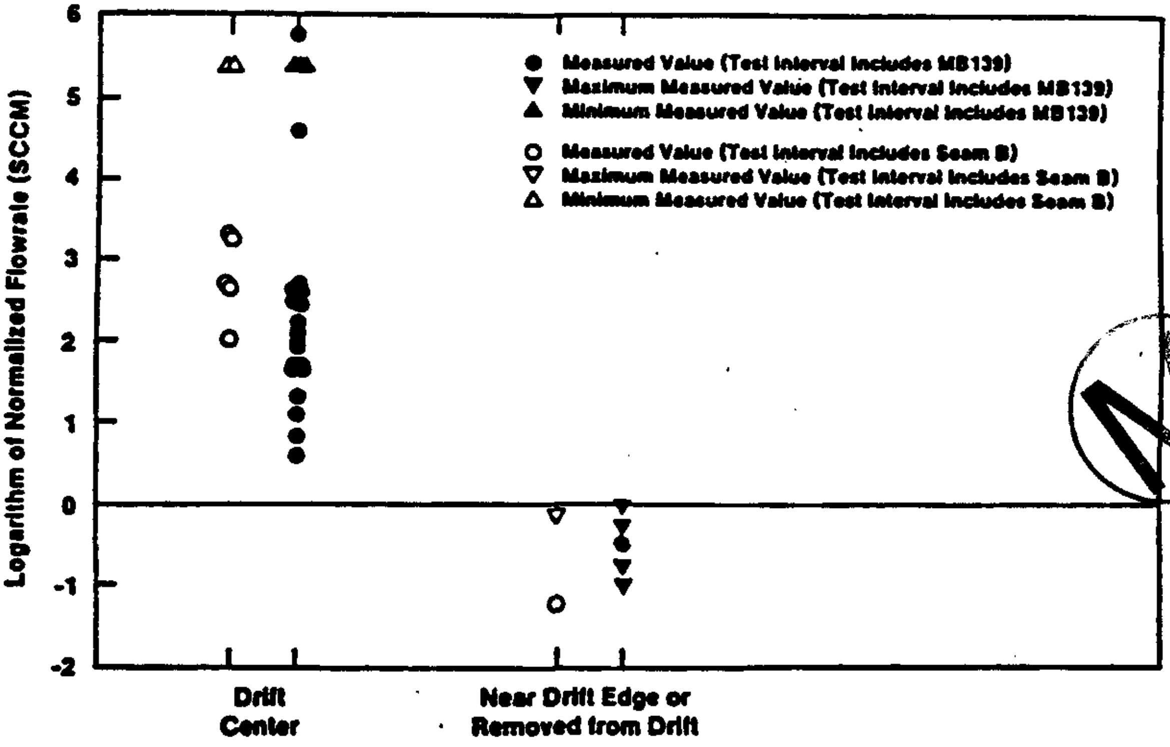


Figure 6-7. Flow Rates in Interbed Layers Within 2 m of Drifts (Borns and Stormont, 1988).

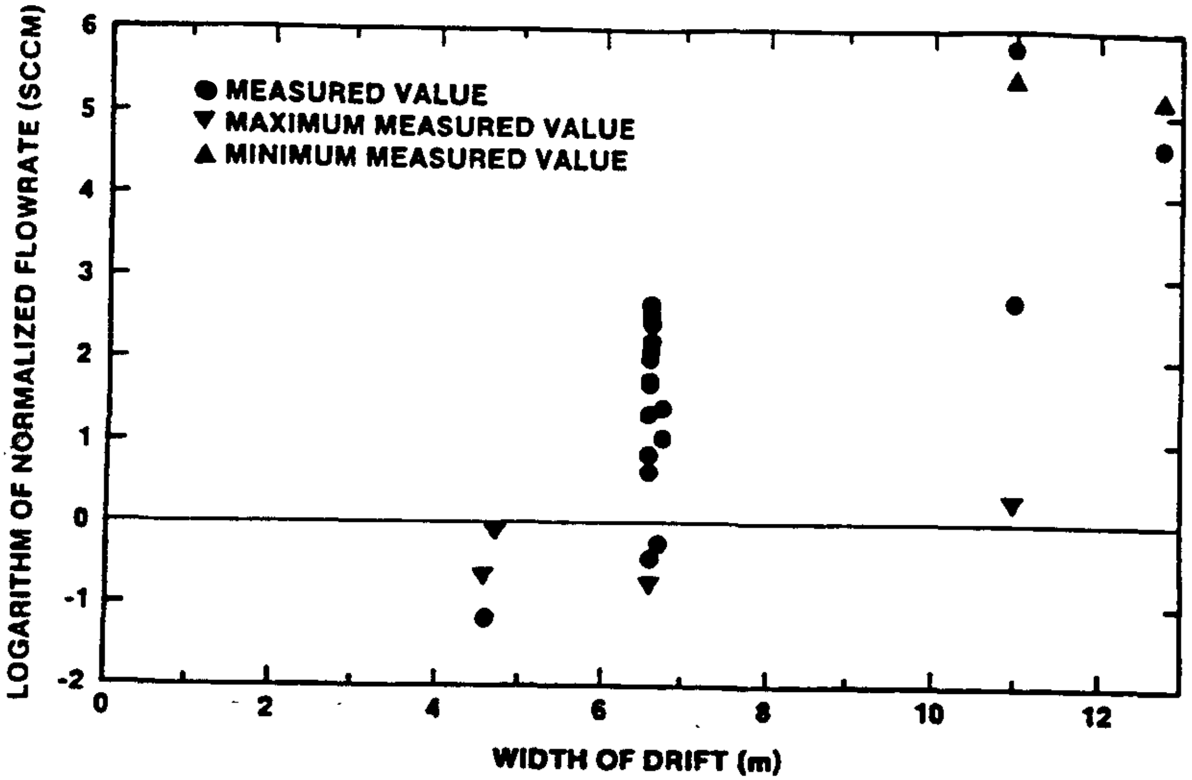


Figure 6-8. Width of Drift Versus Gas Flow Rate in MB139 (Borns and Stormont, 1988).

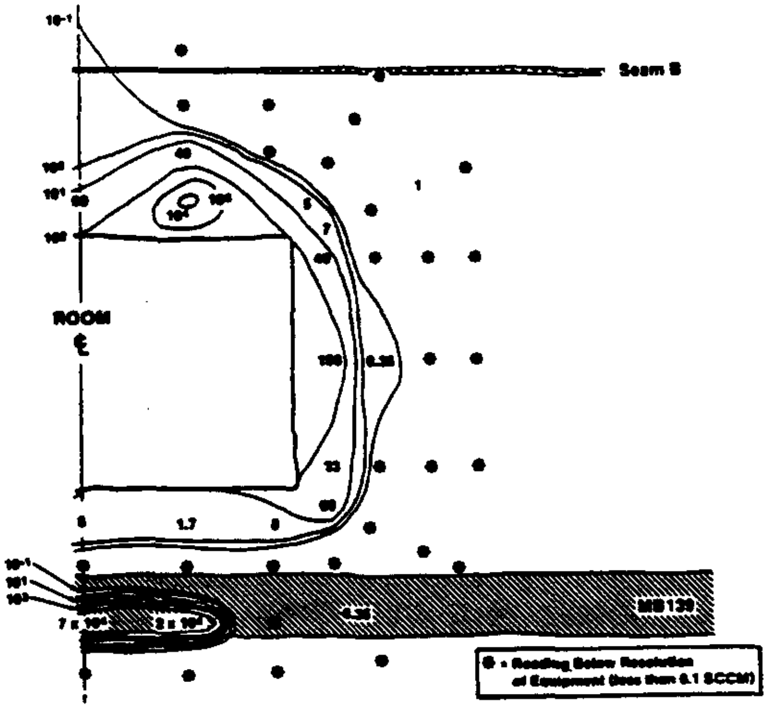


Figure 6-9. N1100 Drift Flow Rate (SCCM) Contours (Stormont, 1988).

observed fractures in the ribs are typically vertical. Separations along stratigraphic features such as interbeds were also observed. Franke (1987) reexamined the fracturing in boreholes over a one-year period and concluded that the rock mass surrounding the excavation continued to fracture over this period. Observed fractures in boreholes increased from 48% of the boreholes in 1986 to 73% of the boreholes in 1987. In older test rooms with larger spans (11 m (36 ft)), 100% of the boreholes had fractures with fracture apertures 2 mm or greater.

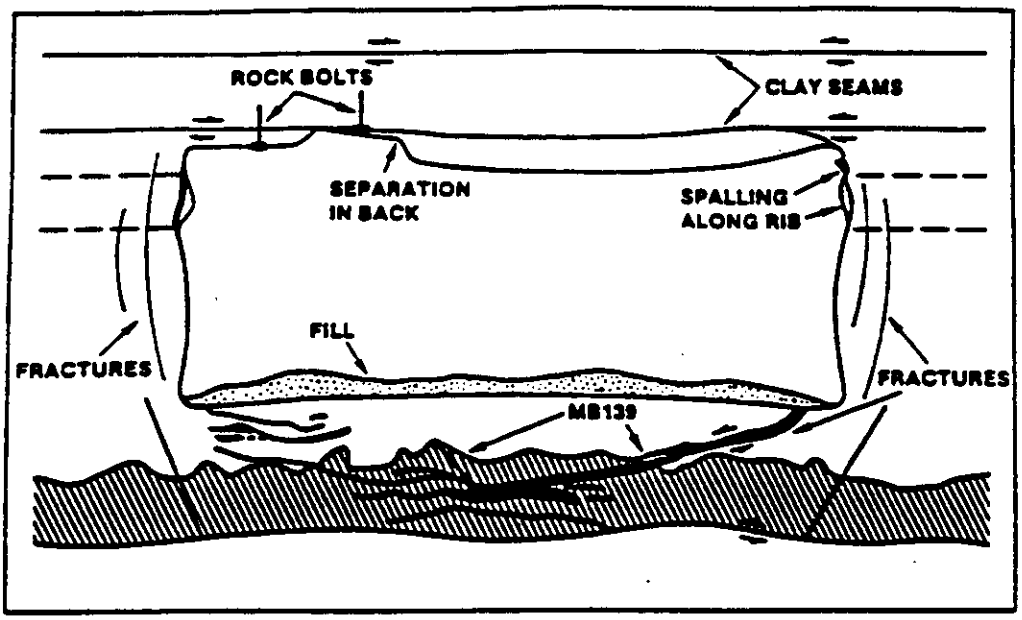


Figure 6-10. Idealized Excavation Effects in a 4 m x 10 m Room (Stormont, 1988).

The fracturing of the rock mass around the excavation results in partially saturated conditions in the rock as a result of drying, exsolution of dissolved gases, and brine inflow. The increased permeability, decreased pore-fluid pressure, and partially saturated conditions all enhance the potential for gas flow pathways between the disposal rooms and nearby higher permeability interbed units (Davies, 1991). Thus, localized regions of increased permeability may exist throughout the repository, supplying potential pathways for contaminant transport. The significance of these pathways relative to repository performance will depend on the ability of the fractures to "heal."

It is anticipated that the fractures in the disturbed zone within the halite interval will eventually close and their permeability approach that of the intact salt (Tyler et al., 1988; Lappin et al., 1989; Sandia National Laboratories, 1993b). Once an excavation is backfilled (with waste, backfill material, or sealing components) and the material is capable of resisting mechanical loading, it is theoretically impossible for the halite to maintain open, interconnected fractures due to salt's plastic deformation behavior and low yield strength. Because of the relatively large porosity in the emplaced waste (0.79) and the crushed salt backfill (0.4), there will be a delay in the closure of the disturbed zone fractures until the final density of the backfilled material is reached, and it resists further creep closure of the disposal room. As the fractures close and the confining stress acting on the fracture increases to lithostatic, the salt is expected to "heal." This process will occur earlier in those sections of the excavation that contain the concrete bulkheads and the crushed salt seal components installed at relatively higher density.

The process of fracture healing or "disturbance reversal" has been demonstrated in the laboratory and in the field. Sutherland and Cave (1979) performed permeability tests with core samples of halite from the WIPP site. The permeability of the samples was relatively high initially, as a result of the mechanical damage that often occurs during collection and transport to the laboratory. After applying a confining stress similar to the lithostatic loads at the repository level at WIPP (14.8 MPa), the permeability of the sample decreased by an order of magnitude. When a confining pressure of 34.5 MPa was applied, the same drop in permeability was observed in six hours. Costin and Wawersik (1980) conducted fracture healing tests using rod specimens of intact salt. The specimens were loaded in tension until failure occurred by compressive loading (up to 35 MPa) at elevated temperatures (up to 100°C) in an attempt to determine whether the fracture would heal. The fractures in tests at the lowest temperature (22°C) and pressure (10 MPa) recovered from twenty to thirty percent of the intact fracture toughness after several days of loading; recovery increases with increasing temperature.

Healing of the DRZ in salt has also been observed in field experiments at WIPP. Test Series B of the Small-Scale Seal Performance Tests used of a 1-m-long concrete plug in a 1-m-diameter borehole (**Figure 6-11**). Gas flow injection and tracer tests were performed thirty days after emplacement to measure the initial permeability of the seal and the types of flow paths present. Very fast travel times (less than twenty minutes) were measured, and flow paths along the rock/seal interface or the adjacent rock mass were observed. Follow-up measurements a year later indicated that the flow paths had been eliminated; there was no tracer movement through any of the seals over a twelve-hour period with a pressure gradient of 2 MPa. (Peterson, Lagus, and Lie, 1987). The reduced permeability is assumed to result from increasing confining stresses around the emplacement hole due to creep closure. Pressure measurements within the concrete seals verified that high radial stresses were generated over the course of the year (Labreche and Van Sambeek, 1988).

6.2.4 Interbeds

The Salado Formation contains a number of interbeds at the proposed depth for the WIPP repository. The design basis assumes that the disposal panels will be excavated within a 7.3-m (24 ft) thick section of halite and polyhalite between anhydrite MB138 and 139. Two of the interbeds, anhydrite B and MB 139, will be within 3 m (10 ft) of the excavation and are likely to be intersected by the fractures in the DRZ. Thus, these features represent potential pathways for the transport of contaminants away from the disposal rooms that could bypass the panel seals. The fracture system in MB 139 below the excavations appears to be extensive and possibly interconnected. Unlike the disturbed zone in the halite rock mass, the fractures in the interbeds are not expected to heal (Stormont, 1988a). Borns (1985) studied the structure of MB 139 from several drillholes in the experimental area of the WIPP underground facility and concluded that many of the fractures existed prior to excavation. The existence of pre-excavation fractures suggests that even if the fractures are closed as the local stresses return to lithostatic conditions, they are unlikely to "heal" and are therefore likely pathways for pressurized gas and brine transport. One option under consideration is the use of cement or crushed salt grouts to seal the interbeds, particularly around the panel seal locations

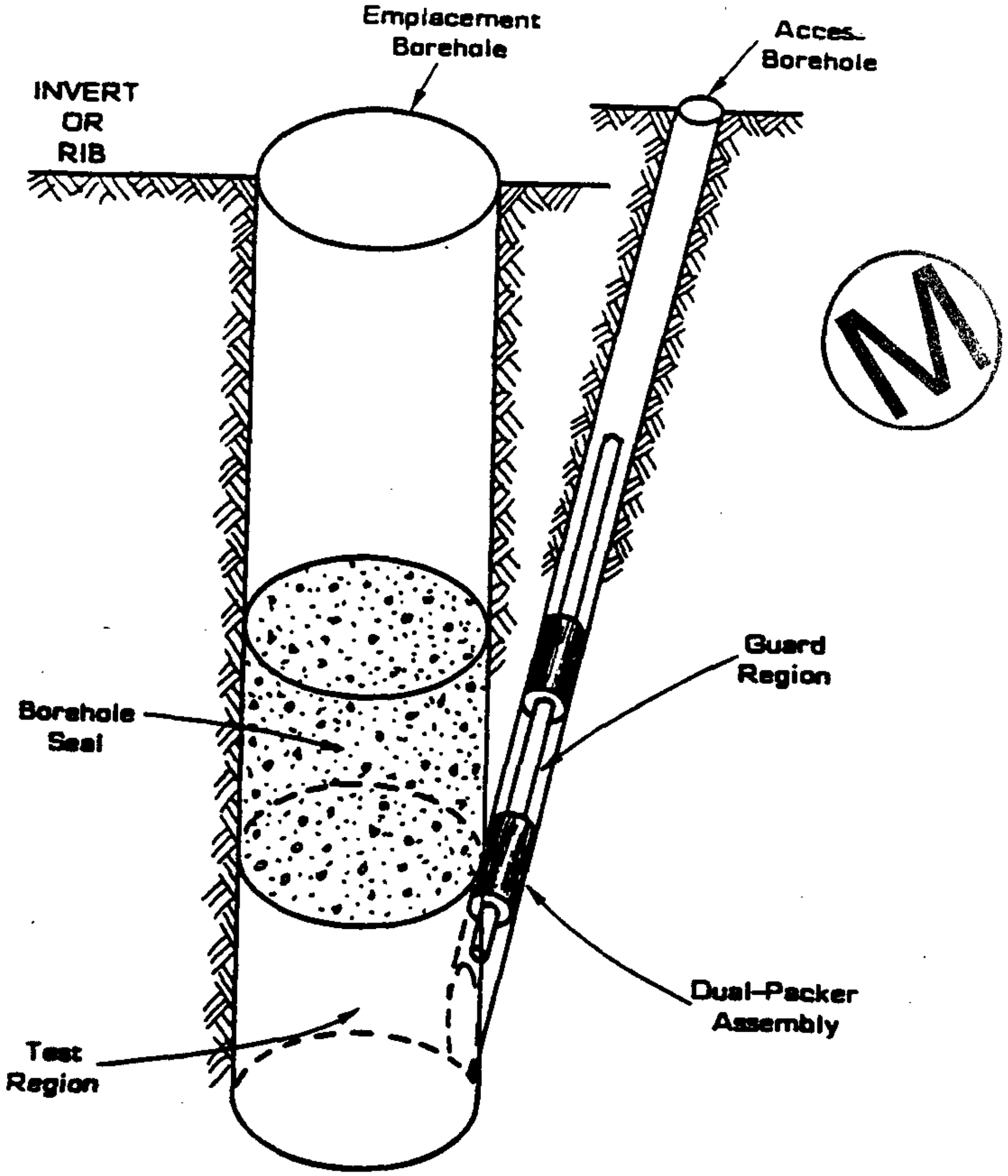


Figure 6-11. Illustration of Test Configuration for the Small-Scale Performance Tests (Peterson et al. 1987).

Effective grouting may be difficult because of difficulties in delivering the grout to the fracture system and the possibility of deformation of the interbed as the rooms close and the surrounding rock mass dilates.

The available pathways for contaminant transport will be a function of time and the processes involved. Immediately after waste disposal, the most likely pathways are through the disturbed zone into the fracture system within the interbeds (MB 139 and anhydrite B) and possibly up the shafts, either through the unconsolidated crushed salt or in the disturbed zone. Brine will tend to flow into

MB 139 and gas into anhydrite B. The consequence of contaminants moving in the interbeds depends on the effectiveness of the shaft plugs and seals and whether the interbeds are intersected by a borehole (human intrusion). Without an additional pathway from the interbeds to the biosphere, the presence of contaminants in the anhydrites is of no real consequence. Assuming the gas pressure in the rooms is less than the sum of the capillary pressure and brine pore pressure in the anhydrites, the fractures in the halite will eventually heal and the pathways to MB 139 will no longer exist. The fractures interconnecting the room to anhydrite B will also heal but rock bolt holes are presumed to provide transmissive pathways to the interbed.

The proposed support system for WIPP consists of 3-m-long (10 ft) rock bolts with mechanical anchors in a 1.5 x 1.5 m (5 x 5 ft) offset pattern. The rock bolts will be left in place after disposal and will eventually corrode, but the remaining material may prevent the halite from forming a complete, low-permeability layer between the room and Anhydrite B. If this conceptual model is correct, the panel seals will be bypassed, first by transport via the disturbed zone to MB 139 and anhydrite B and later through the rock bolt holes to anhydrite B.

It should be noted that Figure 2-1 from Rechard et. al. (1990) (and used in various other WIPP documents including the Test Phase Plan) which is utilized by the PART throughout this document (first used in Figure 4-32) shows rock bolts penetrating two anhydrite layers, creating gas release pathways through both interbeds. Assuming 3-m (10 ft) rock bolts will be used throughout the waste panels, these rock bolts could only penetrate anhydrite B (located approximately 2.5 m (8.2 ft) above the roof) and not anhydrite A (located approximately 5 m (16 ft) above the roof).

The significance of these pathways depends on many related and coupled processes (such as brine inflow, gas-generation rates, threshold pressures in the interbeds, the persistence and interconnectedness of the fractures, human intrusion scenarios, etc.). The question can only be resolved through performance assessment analysis, to determine whether the repository will comply with the performance regulations, or whether changes in the repository design, e.g., eliminating the pathways or the driving forces for contaminant transport will be required.

6.3 SUPPORTING ANALYSES

Engineered barrier performance at WIPP will depend on several related and often coupled mechanisms and processes. SNL has performed a series of analyses to understand the significance of and relationship between some of these factors and to assess the adequacy of the current design for the repository seals. The analyses have focused on the expected creep closure of the underground openings, consolidation of the crushed salt seal components, stresses in the concrete bulkheads, the influence brine inflow may have on consolidation, and the potential for gas and brine migration through the DRZ and interbeds. Summaries of three of these analyses are provided below. Additional analyses are underway to address some of these issues in greater detail. The most important mechanism and processes will be incorporated in the performance assessment models.

6.3.1. Consolidation of Crushed Salt

Sjaardema and Krieg (1977) developed a constitutive model for crushed salt compaction based on the results of small-scale laboratory experiments by Holcomb and Shield (1987) (see Subsection 6.2). The expression was integrated into the finite element code SANCHO and used to investigate the interaction between crushed salt in shaft and drift seals and the surrounding rock mass. The models were then used to investigate whether the consolidation of the crushed salt would retard the rate of creep closure of the shafts and drifts.

The SANCHO model assumed an elastic-secondary creep model with reduced elastic constants for the intact salt. The creep model was calibrated on the basis of the observed closure rates in some of the drifts in WIPP. The results of the analyses indicate that the crushed salt seal will provide little resistance to shaft closure until the density of the crushed salt approaches intact density. The time required for the crushed salt to consolidate to 95% relative density depends on the initial emplacement density. With an initial backfill density of 80%, the calculated time for the backfill to consolidate to 95% relative density is around forty years. This time is reduced to approximately half if the initial density of the backfill material is increased to 85%.

Sjaardema and Krieg also analyzed the interaction between crushed salt backfill and the emplacement drifts. Assuming an initial relative density of 85% (i.e. compacted bricks), the crushed salt seal achieves 95% relative density in approximately twenty years after emplacement, similar to the shaft. Sjaardema and Krieg acknowledge that the analyses have several limitations. The deviatoric model for crushed salt backfill used in the analyses is *ad hoc*. The laboratory tests used to develop the constitutive model for crushed salt compaction did not examine the deviatoric or shear behavior, and the elastic-plastic deviatoric model used in the analyses was chosen for convenience; (i.e., the material parameters for the other deviatoric models were not available). Secondly, the constitutive model for crushed salt compaction is based on laboratory experiments in which the pressures applied to the sample (1.72 MPa to 3.44 MPa) are significantly higher than the calculated backfill stresses (0.5 MPa). Consolidation behavior at the lower pressures was extrapolated and the actual behavior may vary.

Arguello (1988) performed a series of analyses to evaluate the structural interaction between the proposed panel entry seals and the surrounding formation as a function of time. The conceptual design for the panel seals (see Subsection 6.1) consists of a 20 m (6.6 ft) interval of crushed salt between two concrete bulkheads or caps that provide lateral resistance during consolidation of the crushed salt and protect the region from brine inflow. The panel was modeled as a two-dimensional axisymmetric opening using the SANCHO finite element code developed at SNL. The model was used to assess whether the concrete bulkheads will have a significant influence on the consolidation of the crushed salt and to estimate the stress levels that the bulkheads will have to withstand.

The crushed salt portion of the seal was not included in the finite element model because the precompacted crushed salt provides negligible resistance to creep closure until it consolidates to approximately 95% relative density. The change in a density of the crushed salt during room closure was calculated indirectly by using the change in cross-sectional area of the panel opening to calculate the corresponding change in the volume, and hence the density, of the crushed salt. This assumes that the density of the crushed salt is uniform throughout the circular cross-section. The concrete bulkheads were explicitly modeled as linear elastic materials. Properties for the Expansive Salt-Saturated Concrete (Gulick and Wakeley, 1987) were assumed for the analysis. Because of the axisymmetric simplifying assumption, it was not possible to incorporate the stratigraphy at the repository horizon or the opening geometry.

The results of the analysis suggest that effective consolidation (95% fractional density) of the crushed salt is not achievable in the first 100 years over significant portions of the seal if the initial fractional density is less than or equal to 70%. If the initial fractional density is increased to 75%, the salt in the central portion of the seal will reach 95% fractional density in 100 years. For most of the core to achieve 95% density in this time period, the initial fractional density of the crushed 80% is required. Regardless of the initial density or time, the salt in the central portion is more highly consolidated than that adjacent to the caps. The influence of the caps is significantly diminished within one radius into the core and insignificant at 1 diameter into the core.

Based on these results, Arguello (1988) concludes that the end members of the drift seal are unlikely to affect the consolidation of the crushed salt adversely. However, the bulkheads do significantly increase the expected time necessary for the crushed salt core to consolidate to 95% fractional density. A comparison of the results with those of Sjaardema and Krieg (1987) discussed earlier, indicated that the concrete bulkheads approximately double the time required for the crushed salt to consolidate to 95% fractional density. Whether or not this is significant depends on other factors such as the gas pressure in the repository during the first 100 years after seal emplacement, brine inflow rates, etc. The possible impact of high brine inflow rates is discussed below.

The analysis by Arguello also examines the stresses in the concrete bulkheads during closure. The results indicate that the strength of unreinforced concrete may be exceeded. The maximum stresses occur within the first five years after installation of the seal. The maximum radial compressive stress occurs near the ends of the bulkhead and approaches 45 MPa, very close to the unconfined compressive strength for concrete (47.5 MPa). The calculated tensile stresses reach 19 MPa, significantly higher than the assumed tensile strength of 7.1 MPa (15% of the unconfined compressive strength), with tangential stresses (maximum stress of 39 MPa) similar to the radial stresses. On the basis of these results, it appears the bulkheads will require some type of reinforcement to accommodate the tensile and compressive stresses generated during the compaction period. A positive effect of the high compressive stresses in the region of the bulkheads is the potential for the fractures in the disturbed zone to close, reducing the permeability of the annular region in the vicinity of the bulkheads. This will be necessary in order for the bulkheads to protect the crushed salt core from brine during compaction (if it is present in sufficient volumes to be a problem).

The results of the analysis are inconclusive because of the simplifying assumptions contained in the model. The conceptual model of the seal system is assumed to have an axisymmetric geometry (circular), although the drift dimensions are expected to be rectangular (3.7 m by 6.1 m {12 ft by 20 ft}). The axisymmetric assumption also precluded the stratigraphy in the repository horizon from being included in the model of the panel seal. As a result of these assumptions, the stresses around the opening and, therefore, the room closure rates, could vary significantly.

A companion study by Arguello and Torres (1987) investigated the consolidation of a crushed salt panel seal based on a geomechanical analysis using a two-dimensional plane strain model. The drift was modeled as a 3.7-m-wide by 6.1-m-high (12-ft-wide by 20-ft-high) opening containing an infinitely long seal (a result of the plane strain simplifying assumption). The model incorporated reference stratigraphy and material property data for the site and followed a similar procedure used by Arguello (1988) for calculating crushed salt consolidation (i.e., an assumption that the crushed salt provides minimal resistance to room closure until 95% relative density and could be indirectly modeled as an open drift).

The results of the analysis are similar to axisymmetric model; i.e., the time required to reach 0.95 fractional density decreases with increasing initial fractional density. Another finding was that time of seal emplacement (after drift excavation) influenced the time for the crushed salt seal to reach 95% fractional density. The longer the excavation remained open before seal emplacement, the longer the time required for the seal to reach 95% fractional density (assuming the same initial density of the crushed salt seal). For an opening 10 years old or less, an initial fractional density of 80% or higher is required to achieve 95% density in 100 years. While the two-dimensional models discussed above are useful and provide preliminary information concerning the expected behavior of the shaft and drift seals, more realistic three-dimensional models are needed to account for the geometry of the underground excavations and further understanding of the panel seal performance.

Nowak and Stormont (1987) performed scoping calculations of the consolidation of crushed salt shaft seals including brine inflow from the host rock and overlying water-bearing zones in the Rustler Formation. The analysis took into account the potential for brine inflow to retard consolidation of the crushed salt by predicting the decrease in the porosity of crushed salt as a function of time and tracking the percent saturation of the pore space with brine. Closure rate, brine inflow, initial density of crushed salt, and time of emplacement after excavation were varied. The consolidation of the crushed salt was assumed to stop when the salt became saturated with brine.

The results indicate that leakage of brine past the upper seal system (see Subsection 6.1) or from the Salado host rock or interbeds into the shaft seal during the consolidation period could significantly reduce the length of the seal which reaches the reference density of 95% of intact salt. The model assumes that once the brine enters the crushed salt it is prevented from flowing back up the shaft as consolidation proceeds. In order for the lower 100 m (328 ft) of the shaft seal to reach 95% relative density in 100 years, the brine inflow needed to be reduced to 1 m^3/yr and the initial density of the salt seal had to be relatively high (similar to quarried salt blocks). Therefore, the upper seal system in the Rustler Formation and Salado unit must be effective and relatively long-lived (i.e., 200 yr) to protect consolidation of the lower seal. This implies that the current inflow to the lined WIPP shafts (1000 m^3/yr) would need to be reduced by three orders of magnitude. The validity of this deduction depends on the assumption that the brine will be prevented from flowing back up the shaft (i.e., consolidation stops once the salt is saturated with brine), and additional studies may be justified to determine the reasonableness of the hypothesis.

Stormont and Arguello (1988) developed a simple model to predict the volume of water entering the Salado through the upper seal system in the Rustler Formation. The model incorporated shaft seal components (concrete and bentonite), the seal/rock interface, and the DRZ to track the amount of water passing through each element under different conditions. The properties of the seals, interface, and DRZ were varied to determine the sensitivity of the inflow to different conditions.

The results suggest that even when the shafts seals perform perfectly (i.e., achieve design permeability and good seal/rock interface), sufficient amounts of water can enter the salt-filled portions of the shaft if a DRZ is present that allows the groundwater to bypass the seals. The flow rate into the Salado portion of the shaft will depend on the water available from the Rustler and the lowest permeable layer of rock (DRZ) or seal/rock interface it must pass. Therefore, a single layer of low-permeable rock in conjunction with a low-permeable shaft seal (and good seal/rock interface) will severely limit the flow rate through the seal system in the Rustler.

6.3.2. Disturbed Rock Zone and Interbeds

Several other models have been developed by SNL to investigate the potential for gas and brine migration through the DRZ and interbeds as well as shaft and drift seals (WIPP Performance Assessment Department, 1992). The purpose of the modeling was to provide an assessment of the most sensitive parameters affecting gas and brine migration and to help point out significant processes not yet modeled that have the potential to affect regulatory compliance. The two-phase flow code BRAGFLO was used in the analyses.

Three analyses were performed that incorporated different levels of detail about the repository system. The first model examined the potential for lateral migration of gas and brine into the Salado Formation from a representative waste disposal panel. The model did not include repository shafts or access ways (i.e., the shaft-fill material was assumed to have been consolidated to the host-rock porosity and permeability), so that the gas could only migrate laterally toward the subsurface boundary of the land-withdrawal area.

The second model employed a two-dimensional rectangular geometry to provide a more realistic geometric representation of the waste and the underground excavations. The repository system was modeled as a series of waste, panel seals, backfill, and shaft regions, with possible vertical and horizontal (via the excavations) flow paths. The objective of the model was to determine threshold seal permeability and gas-generation parameters for gas flow through the repository and up the equivalent shaft. The repository shafts were modeled as a single "equivalent" shaft containing a seal whose permeability decreases with depth. The rock surrounding the shaft was assumed to be undisturbed; for example, a DRZ was not included around the shaft.

The third model was similar to the second, except that it included an additional interbed and a modified seal design. Instead of a long shaft seal consisting of compacted crushed salt, a shorter (10 m {33 ft}) high-quality seal with a very low permeability was assumed. The remainder of the shaft was assumed to be filled with backfill.

The DRZ around the underground openings (excluding the shafts) was included in the models and was represented as an area of increased permeability and porosity. The properties of the DRZ and interbeds were held constant; i.e., possible healing of the DRZ due to salt creep and pressure-dependent fracture propagation in the anhydrite interbeds was not included. The importance of these and other modeling assumptions was not quantified.

Of the sixty Monte Carlo realizations of the sampled parameters for the first model, 13 resulted in the migration of gas through the interbeds toward the far-field boundary. Only one realization resulted in gas migrating into the element in the model grid containing the 2.4 km (1.5 mi) disposal-unit boundary. The results were most sensitive to the anhydrite rock properties (porosity, permeability, and capillary threshold pressure), the rate and amount of gas generated, the two-phase flow properties of a brine/gas system, and the far-field boundary pressure. Gas migration in the anhydrite was inhibited because of the low anhydrite permeability and associated high values of capillary threshold pressure assumed in the model. The permeability determines the resistance to gas flow once the capillary forces necessary to displace the brine are exceeded.

Because the second model assumed relatively low permeability for the halite in the DRZ around the disposal rooms and drifts, gas flow was limited to a path through the waste and seal components in the rooms and shaft. The shaft was modeled as four sections representing regions having different permeabilities and porosities. Of the twenty-two Monte Carlo realizations analyzed, sixteen resulted in gas migrating out of the shaft and into the Culebra. In those where there was little or no gas flow, the permeability of the lowest portion of the shaft was less than 10^{-19} m^2.

In the third model, gas could migrate through the shaft and the interbeds. A total of 60 realizations was performed. Gas was predicted to penetrate the shaft seal in 15 of the realizations, resulting from cases having very high values for parameters that encourage gas production, such as high gas-generation rates, and for the parameters controlling brine inflow. The realizations in which there was no gas released from the shaft generally represented situations where the gas-generation rates were low or the amount of brine available for corrosion reactions was limited. Gas flow in the interbeds exceeded the 2.5 km (1.5 mi) boundary in only one of the realizations although the volume of gas reaching the boundary was very small. Gas flow into the interbeds occurred in only six of the realizations. These cases corresponded to simulations with high panel pressures and low threshold displacement pressures. Thus, in most of the realizations, the panel pressure was below the lithostatic pressure due to the large storage volume within the repository. However, the model did not include creep closure, which could greatly reduce the available storage volume and result in significantly higher panel pressures. The model also did not include enhancement of the interbed permeability from pressure-related fracturing.

Brine migration was also examined in the third model. The maximum quantity of brine driven out of the waste was 3,880 m^3. None of the brine entered the interbeds because the storage capacity of the DRZ was sufficiently large. These results are questionable for the same reason as the gas migration results: the absence of creep closure in the model provides unrealistic pore space in the waste panel for a majority of the time being modeled; (creep closure of the waste panels is expected to be largely complete in approximately 100 years after disposal).

In general, the longer shaft seal was more effective in preventing gas migration up the shaft. While the shorter seal had a lower permeability than the long seal, the remainder of the shaft was assumed to offer little resistance to flow (i.e., a high permeability). Therefore, the long seal provided a much longer flow path through low permeability materials.

On the basis of these analyses, the following parameters were found to be the most important:

- far-field pore pressure in the interbeds,
- gas production rate (from corrosion and microbial degradation),
- initial brine saturation in the waste,
- permeability of the shafts,
- intrinsic permeability of the interbeds.

The authors recognized the limitations of the models used in the analyses and recommended several activities to improve confidence in their ability to predict the behavior of the repository system. These involve making more realistic conceptual models of repository seals and the surrounding rock mass, including pressure-dependent fracturing of the interbeds and the time dependent behavior of the DRZ (healing), as well as additional research to better understand the parameters controlling gas generation.

None of the conceptual models describing shaft and drift seal behavior have been incorporated into the performance assessment analyses for preliminary comparison with 40 CFR 191 or 40 CFR 268.6. The existing models used for performance assessment analyses do not include a representation of the shaft, borehole, or drift seals. The primary reason for not including engineered barriers is related to budget constraints and the need to address other aspects of the repository system that were assigned a higher priority (Anderson., 1993).

However, the importance of engineered barriers is recognized by the scientific and management staff supporting WIPP and these features will be incorporated in subsequent performance assessment analyses. Sandia National Laboratories has identified a number of issues that need to be resolved to provide a high degree of confidence in the shaft, drift, and panel seal performance (Tyler et al., 1988). The issues define the areas where additional testing or technology development and demonstration may be needed.

- Water inflow from the overlying formations must be controlled for the initial period after installing the shaft seal until the crushed salt component has been compacted to the design density.
- The DRZ around the shafts and drifts must be characterized to determine whether it represents a potential flow path around the seals and whether remedial work is necessary.
- The creep rate of salt around the shafts and drifts must be measured to determine when the crushed salt will be consolidated and form an effective seal.
- Brine inflow from the Salado Formation must be characterized to determine its likely effect on seal formation.

The significance of the above issues is difficult to assess until the seal systems are incorporated in the system model for WIPP. While the subsystem models (discussed in Subsection 6.3) provide useful insight into the sensitivity of the seal performance to local conditions it is not possible to identify and prioritize additional studies without knowing the contribution of the various features and processes to system performance.

6.4 SUMMARY

The performance of engineered barriers (seals) is difficult to predict in a performance assessment analysis because they rely heavily on other poorly understood mechanisms and processes in the natural system. Barrier performance is determined by a combination of closure of the underground openings by creep of the salt, compaction of crushed salt, the presence of brine during compaction, gas-generation rates, the extent and healing of the disturbed zone, and the permeability of interbeds. While the laboratory and analytical studies performed by the WIPP Project and Sandia National Laboratories in particular are impressive and represent significant progress in the understanding of these processes, additional work is needed before a defensible compliance application can be completed.

In the current design for the engineered barrier system, the primary component for sealing the shafts and panel entryways is crushed salt. The material has several desirable properties such as chemical compatibility with the host rock, plastic behavior with the ability to flow under stress, and low permeability when it is compacted sufficiently under high enough stresses. The above properties make crushed salt an excellent candidate for use in the engineered barriers for WIPP. However, several issues may need to be resolved to reduce the uncertainty in the long-term performance of the WIPP repository and the ability of the system to meet the performance requirements in 40 CFR 191 and 40 CFR 268. These include the capacity of crushed salt to achieve a relative density of 95% in brine saturated conditions, the time and conditions necessary for the DRZ in the halite and polyhalite portions around the excavations to heal and approach intact conditions, and the hydrogeologic properties of the interbeds, particularly anhydrite B and MB 139.

The results of the scoping calculations by Nowak and Stormont (1987) on the consolidation of crushed salt shaft seals in the presence of brine inflow indicate that leakage of brine past the upper seal system into the shaft seal during the consolidation period could significantly reduce the length of the crushed salt seal that reaches the reference density of 95% intact salt. In order for the lower 100 m (33 ft) of the shaft seal to reach 95% relative density in 100 years, the brine inflow rate must be reduced to one m^3/yr. Therefore, the upper seal system in the Rustler Formation and Salado unit must be relatively long-lived (i.e., 200 yr) and capable of reducing the current inflow rate in the lined WIPP shafts (1000 m^3/yr) by three orders of magnitude. The validity of the above conclusion depends on the assumption that the brine will be prevented from flowing back up the shaft. Additional in situ experiments, perhaps similar to the Series C studies, are recommended to test this hypothesis. If consolidation is effectively halted once the pore volume of crushed salt is saturated, additional seals testing in the Rustler Formation may be warranted.

The DRZ will provide a pathway for brine and gas migration from the disposal rooms to nearby interbeds (MB 139 and anhydrite B). In the halite and polyhalite portions of the rock surrounding the excavations, the DRZ is expected to heal with time and eventually prevent further transport through this pathway. However, an additional pathway to anhydrite B is expected through the rock bolts holes that intersect the overlying interbed. Therefore, the pathways for contaminant migration are likely to change during the first several hundred years after disposal. Immediately after closure, gas and brine will be able to flow through the DRZ into MB 139 and anhydrite B. As the DRZ heals, gas and brine movement will be limited to anhydrite B. Because the storage and thickness of MB 139 are expected to be significantly greater than those of Seam B, the extent and pressure of any gas or brine in the interbeds will depend in part on the time MB 139 is hydraulically connected to the waste panels.

In situ tests are planned to measure the characteristics and behavior of the fractured anhydrites (US Department of Energy, 1992) and should improve the understanding of the potential for and extent of contaminant transport. In addition to the studies already planned, a large-scale field test is recommended to provide empirical information on the healing of the DRZ in the halite and polyhalite host rock. This might involve a rigid bulkhead in the experimental area of the WIPP facility. After characterizing the DRZ in the salt and interbeds, a bulkhead would be installed and changes in the DRZ properties monitored. The bulkhead would simulate DRZ healing after room closure is complete and the stress state returns to lithostatic conditions.

As mentioned earlier, it is difficult to reach firm conclusions about the adequacy of the seal system until the performance assessment analysis incorporates the most important aspects of these components. Discussions with project staff indicate this effort will be given a high priority beginning in FY 94. At a minimum, simplified representations of the shaft and panel entryway seals, DRZ, and interbeds should be incorporated in the system model in the next performance assessment iteration to determine the sensitivity of the repository performance to the parameters and processes involved.

7.0 REPOSITORY SCENARIOS

This section outlines the approach used for performance assessment (PA) of the post-closure repository behavior of the waste disposal system, considering both undisturbed and disturbed repository scenarios. Subsection 7.1 discusses the base-case, or undisturbed, scenario, in which only naturally occurring events and processes are assumed to take place. Three cases of migration in the repository are examined in two-dimensional simulations. Fully coupled, three-phase (salt, brine, gas) models have not been implemented in the PA, nor has the time-dependent behavior of the disturbed rock zone (DRZ). Subsection 7.2 discusses PA's approach to addressing the probabilities and consequences of inadvertent human intrusion during the 10,000 year period mandated by the regulations (i.e., disturbed repository scenarios). Three inadvertent drilling scenarios are examined. Intrusion probability models are discussed, and direct releases to the surface considered.

7.1 SUMMARY OF UNDISTURBED SCENARIO AND PERFORMANCE ASSESSMENT

The base-case or undisturbed summary scenario, with which this subsection is concerned, describes the waste disposal system from the time of decommissioning and incorporates all expected changes and uncertainties in the system for 10,000 years. Because of the stability of the natural system, all naturally-occurring events and processes are nondisruptive (Marietta et al., 1989; PA, 1992a). After the repository is filled with waste, the disposal rooms are backfilled and seals are emplaced in the shafts and access drifts. Because of the high lithostatic pressure at repository depth, closure due to salt creep is expected to consolidate crushed salt seals to the nearly impervious behavior of intact salt. Simultaneously, drums housing the as-received waste will collapse and their contents will compact to materials of reduced porosity and permeability. Closure will occur in less than 100 years, unimpeded by brine inflow or gas generation, although these characteristics may affect subsequent repository behavior.

The Performance Assessment Department of the Sandia National Laboratories has considered gas and brine migration from the repository in preliminary sensitivity analyses related primarily to the no-migration requirements of 40 CFR 268.6(a). Three cases of migration in the undisturbed repository (Subsection 6.3.2) were addressed in the two-dimensional simulations (PA [RCRA], 1992). Using a probabilistic approach for analyzing uncertainty in the performance and the BRAGFLO two-phase flow code (PA, 1992, 2, App. A), Case 1 permitted only lateral gas and brine migration along MB 139 and anhydrite layers A and B by omitting shaft seals; vertical migration through the overlying halite does not occur. Cases 2 and 3 investigate gas and brine flow up the shaft as well as laterally. Case 2 analyzes migration from waste separated from the shaft by a varying number of panel seals and then up a shaft sealed by four sections of crushed salt whose permeabilities decrease to that of the intact salt. Case 3 investigates the effect of a single 10-m-thick (33-ft-thick), high quality shaft seal, and ineffective panel seals, and expands gas storage area, by adding MB 138, the experimental area and the transition (depressurized) zone between the DRZ and intact halite. However, void volume of the DRZ is not included in estimates of the final waste porosity, and possible gas pressure-dependent fracturing of anhydrite is not considered. Room porosities calculated are based on sampled volume fractions of corrodible metal and biodegradables, and they are the ones required to store all gases generated at lithostatic pressure in a brine-free repository.

Simulations predict high relative gas saturations in the waste so that, although gas generation takes place dominantly under humid rather than inundated conditions, all metal was corroded within 10,000 years. Lateral migration of the gas was generally very limited in all three cases because the room gas pressure did not rise high enough to force the gas-brine interface out through the interbeds. Gas flow up the shaft, driven by the pressure gradient between the disposal room and the Culebra Dolomite Member of the Rustler Formation, proved to be the principal migration pathway. For Case 2, gas release to the Culebra was unlikely for a lower shaft seal with a permeability less than 10^{-19} m^2, and for Case 3, a permeability of less than 5×10^{-21} m^2 is required; both estimates ignore leakage around the seals. Finally, selected simulations show that brine which has been in contact with the waste has not migrated beyond the DRZ in 10,000 years (PA [RCRA], 1992, p. 1-6).

The most recent model (PA, 1992, 1) accounts for creep closure of the waste disposal rooms by using results from the geomechanical code SANCHO (PA, 1992, App. B) to estimate waste porosity as a function of pressure. Fully-coupled, three-phase (salt, brine, gas) models have not yet been implemented in the performance assessment nor has the time-dependent behavior of the DRZ. As regards the latter, it was suggested in Subsection 5.5 that the DRZ might self-seal in 100 years, encapsulating the waste in each room at a gas pressure near 1 MPa. For this humid-environment, gas-generation model, gas pressure would build up until vented along rock bolts to anhydrite B. If permeabilities and pore and threshold pressures permit sufficiently rapid migration of the gas along these layers, and along thin clay layers exposed in the disposal rooms, then gas releases might be sufficient to maintain gas pressure in the room at or below the equilibrium lithostatic pressure. So long as the VOC and radionuclide content of gas that might escape to the accessible environment remains below 40 CFR 268 and 40 CFR 191 limits, the repository poses no threat; certainly, contaminated brine would not migrate beyond the DRZ.

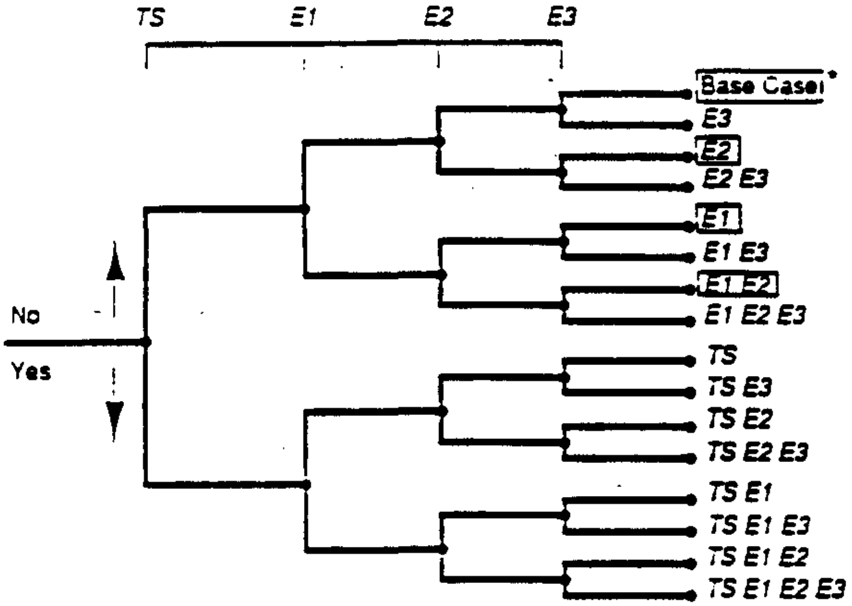
This humid model assumes, with considerable experimental basis, that the moistened crushed salt backfill will reconsolidate to a fractional density greater than 95% of intact salt. Much of the 50 m^3 of brine flowing into the room in the 100-year period could thus be isolated in pores of the backfill, lowering the gas pressure in the waste and disposal room still further (Nowak et al., 1988). The model is in keeping with the statement by Mendenhall et al. (1991, p. 3-14): "As we learn more about the host rock hydrologic properties and about coupling geomechanical and fluid flow behavior, the trend seems to indicate that very low permeability host rock, deforming room boundaries, and gas pressurization will inhibit brine flow into the repository and thus limit gas generation."

7.2 SUMMARY OF DISTURBED REPOSITORY SCENARIOS AND PERFORMANCE ASSESSMENT

7.2.1 Human Intrusion Scenarios

The 40 CFR 191 Appendix B states that "... inadvertent and intermittent human 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." Performance assessments for 40 CFR 191 currently concentrate on inadvertent human intrusion by exploratory drilling (for fossil fuels, water, injection disposal), which has been demonstrated to be the only event likely to lead to radionuclide releases near, or in excess of, regulatory limits (WIPP PA, 1992, 1, ch. 4). If the waste-disposal panels are penetrated by a borehole, then radionuclides may reach the accessible environment either directly as particulate matter (e.g. cuttings) and brine in the circulating drilling fluid or indirectly through transport by groundwater flowing through overlying transmissive strata.

Figure 7-1 shows the logic diagram for WIPP performance assessment; no temporal relationships between events and processes are implied by their sequence across the top of the diagram. To date, only the base case and inadvertent drilling scenarios E1, E2 and their series combination scenario, E1E2, have been analyzed.



Summary Scenarios
TS - Potash mining
E1 - Intermittent exploratory drilling into room and pressurized brine pocket in Castile Formation
E2 - Intermittent exploratory drilling into room
E3 - Withdrawal wells for usable water

Figure 7-1. Potential Scenarios for the WIPP Disposal System (PA, 1992, 2).

The summary scenario E1 describes one or more exploratory boreholes that penetrate a waste-filled panel and a pressurized brine reservoir in the underlying Castile Formation (**Figure 7-2**). Scenario E2 describes events whereby one or more boreholes penetrate a waste-filled panel but do not penetrate pressurized brine below the repository horizon (**Figure 7-3**). For both E1 and E2 events, initial radionuclide releases result directly from the drill bit intersecting waste (cuttings, cavings, spalling). After drilling is complete, the holes are assumed to be plugged and abandoned, with drilling mud and plugs that degrade (except those above the Culebra) remaining in the borehole. The boreholes are assumed to remain propped open by fill, and a single plug above the Culebra is assumed to remain intact, diverting any flow up the borehole into that transmissive pathway to the accessible environment. Rate of flow depends on the hydraulic properties of the borehole fill and head difference between the Culebra and injected brine (E1) and that between the Culebra and repository (E2).

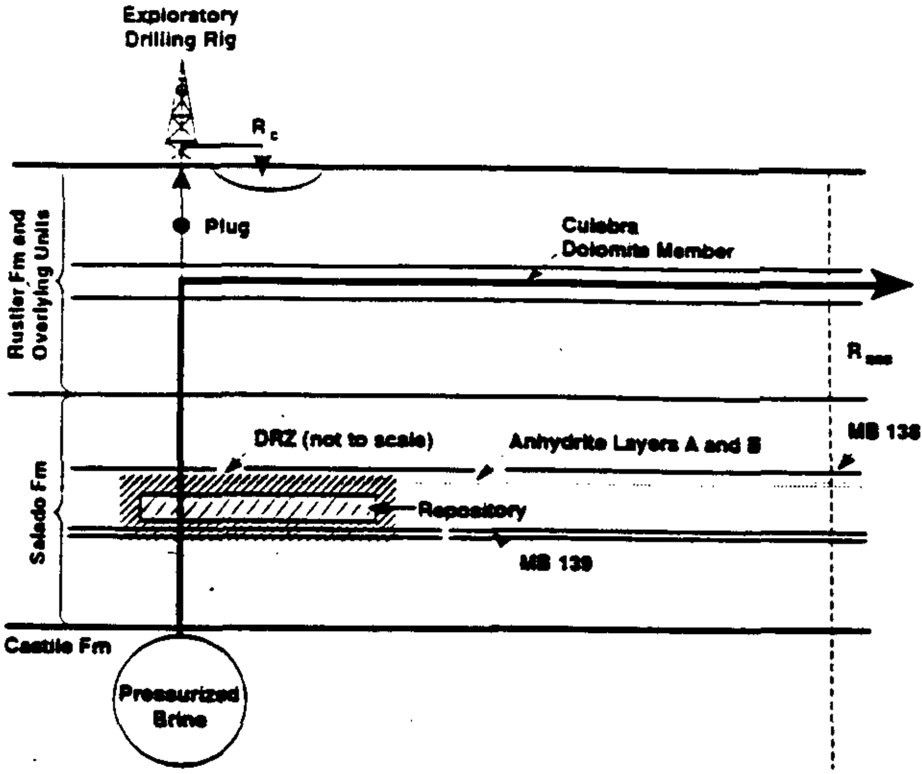


Figure 7-2. Conceptual Model for the E1 Scenario. R_c is Release of Cuttings and R_{acc} is Release to the Accessible Environment. Plug shown is assumed to remain intact for 10,000 years (PA, 1992, 2, Figure 4-2).

Scenario E1E2 consists of two boreholes that have penetrated waste-filled rooms or drifts in the same panel, one having also penetrated pressurized brine below (Figure 7-4). However, the intact plug for E1 (left-hand well in Figure 7-4) has been placed below the Salado-Rustler contact so as to maximize flow from the Castile pressurized brine through the waste into the borehole to the Culebra. For this scenario, intact plug placement is critical. Sequence of placement is not, however, and therefore analyses of scenario E1E2 assume that both boreholes are drilled nearly simultaneously. Scenario E1E2 reverts essentially to E2 when the driving pressure of the underlying brine is depleted. However, brine pressure depletion is not considered in current PA analyses. (Beauheim et al., 1993)

7.2.2 Subsurface Brine Transport Simulations

E2-type intrusions are simulated explicitly using the BRAGFLO, SANCHO and PANEL computer codes (Table 2-1). E1-type scenarios are not simulated explicitly. Consequences for E1 are assumed to be the same as for E2 intrusions but the probability of the E2-type is greater for most

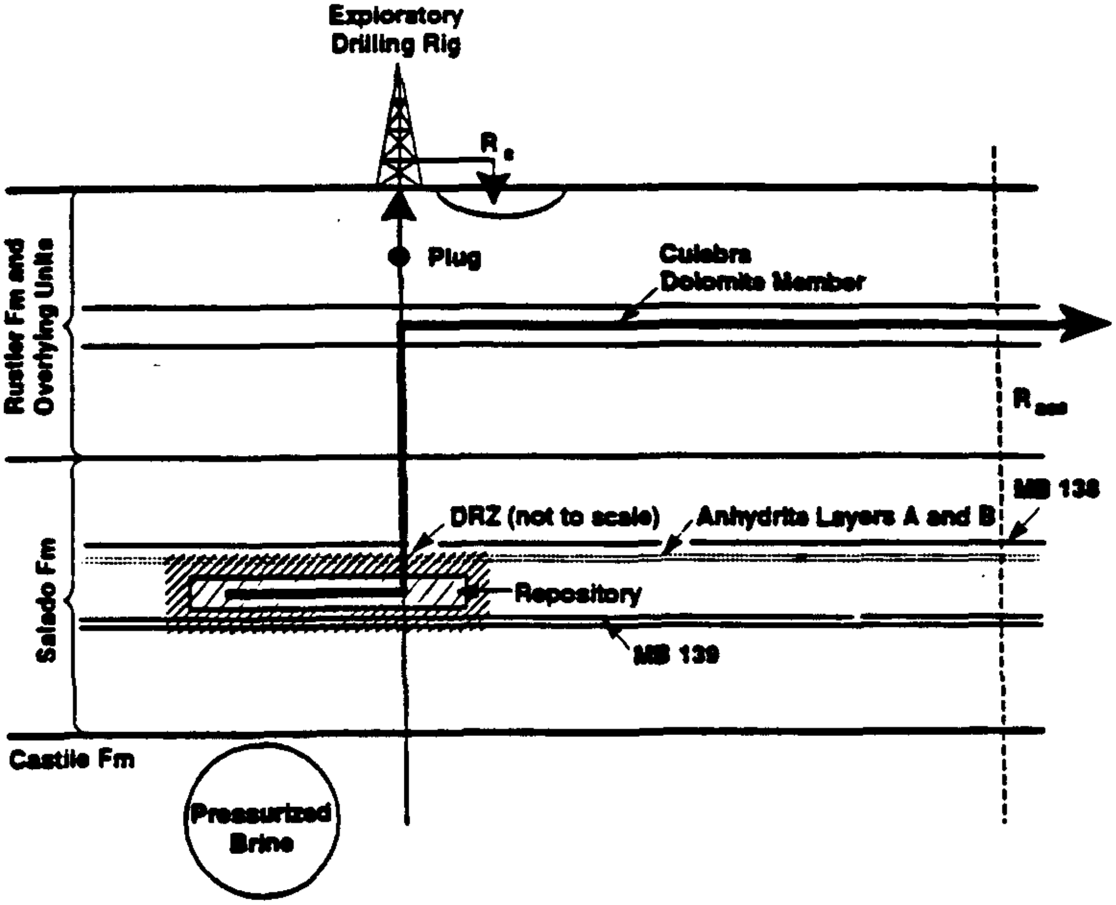


Figure 7-3. Conceptual Model of Scenario E2

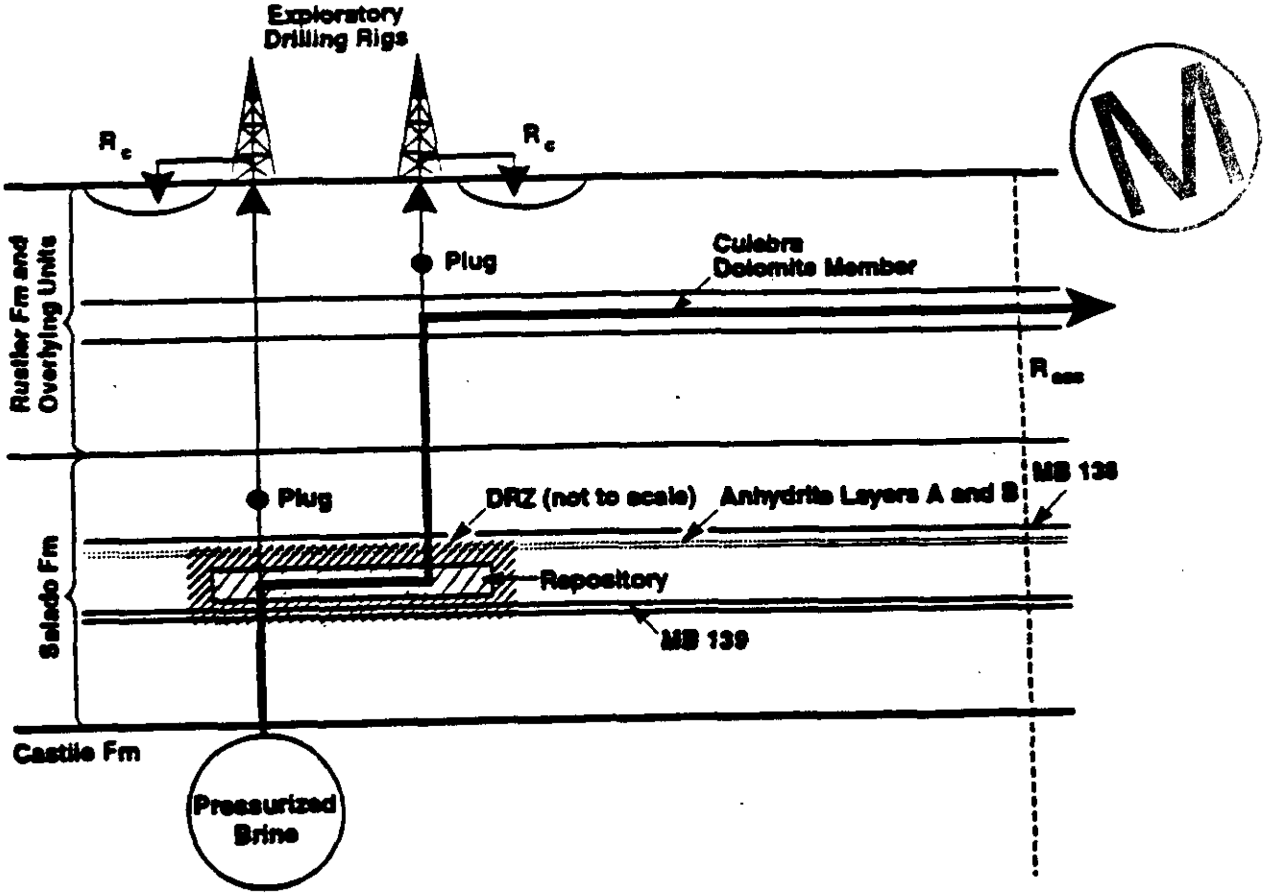


Figure 7-4. Conceptual Model of Scenario E1E2.

realizations. E1E2-type intrusions are not simulated explicitly because the axisymmetric cylindrical geometry used for BRAGFLO cannot readily accommodate two intrusion boreholes. This scenario is simulated using a single borehole and the assumption that all brine in the waste-filled panel mixes with all Castile brine flowing up the borehole. Because the flow path between the two boreholes is omitted, this simplification overestimates both the amount of waste dissolved and the rate of flow (WIPP PA, 1992, 2, ch. 4).

Following the occurrence of an E2 or E1E2 inadvertent intrusion scenario, flow of brine through a collapsed WIPP panel and up an intrusion borehole may result in transport of dissolved radionuclides through transmissive members of the Rustler Formation. Radionuclide transport in the Culebra dolomite, identified as the most highly transmissive member, has been described by three alternative conceptual models (Subsection 4.3). The fracture-only (single porosity) model—transport through unlined fractures only, with no physical or chemical retardation—is regarded as unrealistic. The dual-porosity, K_d = 0, model (**Figure** 7-5) treats the Culebra as a dual-porosity medium with transport occurring along clay-lined fractures and diffusion occurring into the clay and dolomite matrix causing physical retardation; distribution coefficients, K_ds, are assumed to be zero, and no chemical retardation occurs. Available data from well tests support this model. The dual-porosity, $K_d \neq 0$ conceptual model is identical, except that chemical retardation does take place both in the clay linings and the dolomite matrix. This model is preferred by the WIPP PA department but it is not yet fully supported by available data.

7.2.3 Intrusion Probability, Release Modes, and Consequences

Intrusion probability models are based on the assumption that intrusion events will follow either a time-independent (λ_o) or a time-dependent (λ_t) Poisson process. On the basis of the λ_o model and the intrusion density that must be considered for 10,000 years, 30/km^2 (U.S. EPA, 1985, p. 38089), the largest number of intrusions for seventy realizations used in the 1992 analyses is ten.

This number is reduced to four for the λ_t model primarily because of the predicted efficacy of passive markers and because resource exploration and exploitation (especially for hydrocarbons) is likely to diminish and then end within 500 years as the resource potential is evaluated and the energy economy ends its reliance on hydrocarbons (Hora, 1992). The λ_t model, scaled to reflect the fractional area of overlap of waste panels and underlying brine pockets, is the preferred PA model for 1992 PA calculations (WIPP PA, 1992, 2, ch. 5).

The 1992 PA considers direct releases to the surface by cuttings, cavings and borehole fluids associated with the drilling process and indirect releases to the accessible environment by subsurface transport up the borehole and through the Culebra dolomite. Because of the radioactive decay history of the inventory, direct releases are more sensitive to the time of intrusion during the first 1000 years than are indirect releases (because of long periods of subsurface transport). Therefore, direct releases to the surface have been considered for intrusions at six different times after decommissioning (100, 175, 350, 1,000, 3,000 and 7,200 years), whereas a single time (1,000 years) is considered for subsurface releases. For comparison with EPA Containment Requirement 40 CFR 191.13(a), releases are plotted as Summed Normalized Releases (SNR) against the Probability of Release (POR) on mean Complementary Cumulative Distribution Function (CCDF) diagrams (§ 2).

Uncertainties introduced into cuttings releases by choices of single or multiple intrusions and choice of intrusion probability model are illustrated in **Figure 7-6**. The larger number of intrusions for the time-independent (λ_o) case leads to much higher probabilities of release than for the time-dependent λ_t) model. A single intrusion at 1,000 years for the λ_o model also results in appreciably higher release probabilities than for λ_t but only slightly lower probabilities than for the multiple-intrusion λ_o model. For all three cuttings release models, the CCDF curves show that expected releases fall two orders of magnitude or more below the EPA limit. (1992 PA, Volume 1, pg. 5-6)

Subsurface releases resulting from an E1E2-type intrusion at 1000 years, with contaminated brine transport up the borehole and through the Culebra by means of the three conceptual flow mechanisms, are as shown by the CCDF curves of Figures 7-7 and 7-8. For the single-porosity, fracture-only flow model (**Figure 7-7**), subsurface releases clearly dominate cuttings releases (Figure 7-6, one intrusion) and, for the time-independent (λ_o) model, they are less than one order of magnitude below the EPA limit at a probability of 10^{-3}. Changing to a dual porosity, $K_d = 0$ (physical but no chemical retardation) transport model for λ_o intrusion reduces the CCDF to more than one order of magnitude below the limit at all

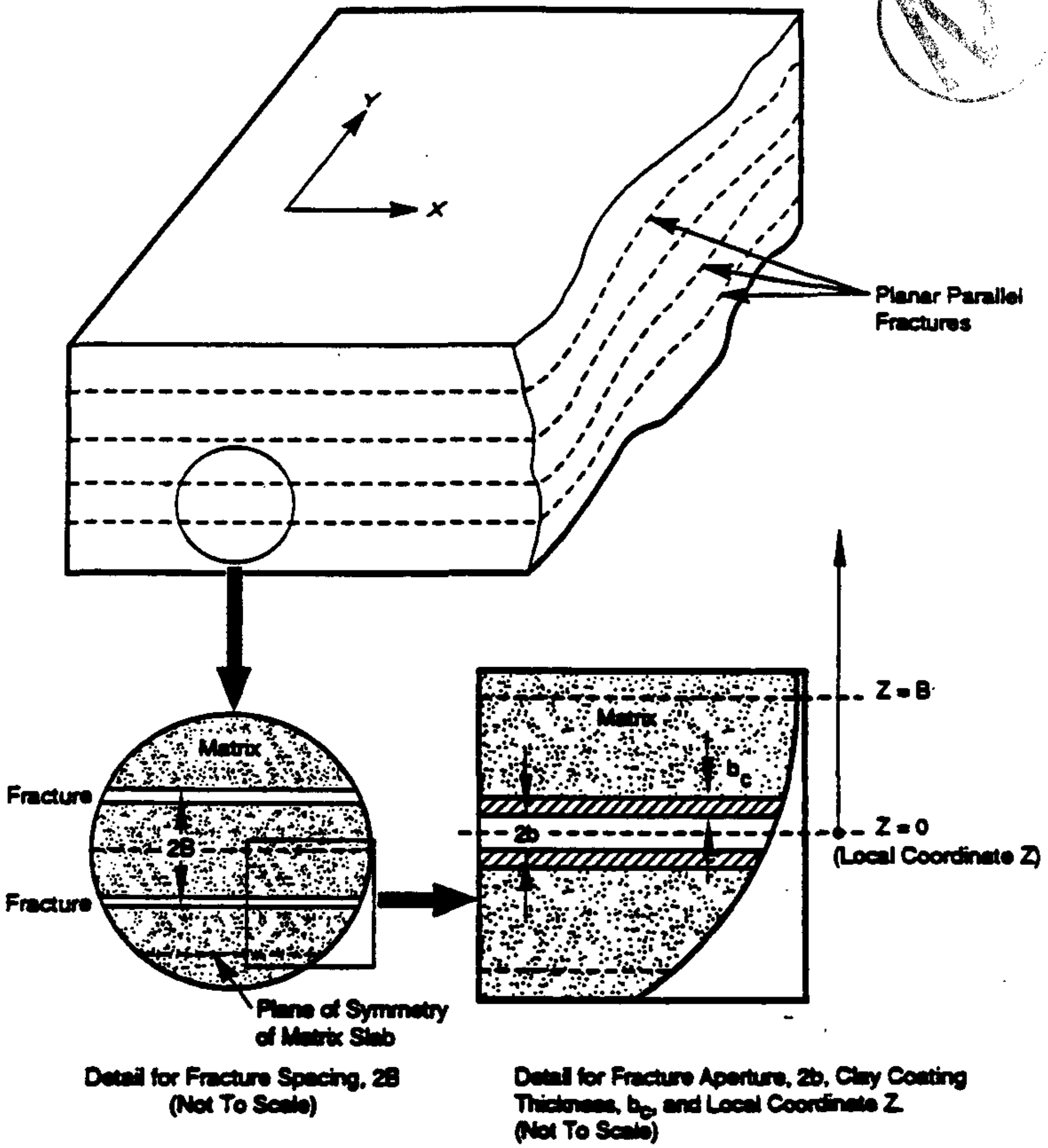


Figure 7-5. Conceptual Hydrologic Model of the Culebra Dolomite (PA, 1992, 2, Figure 7-4).

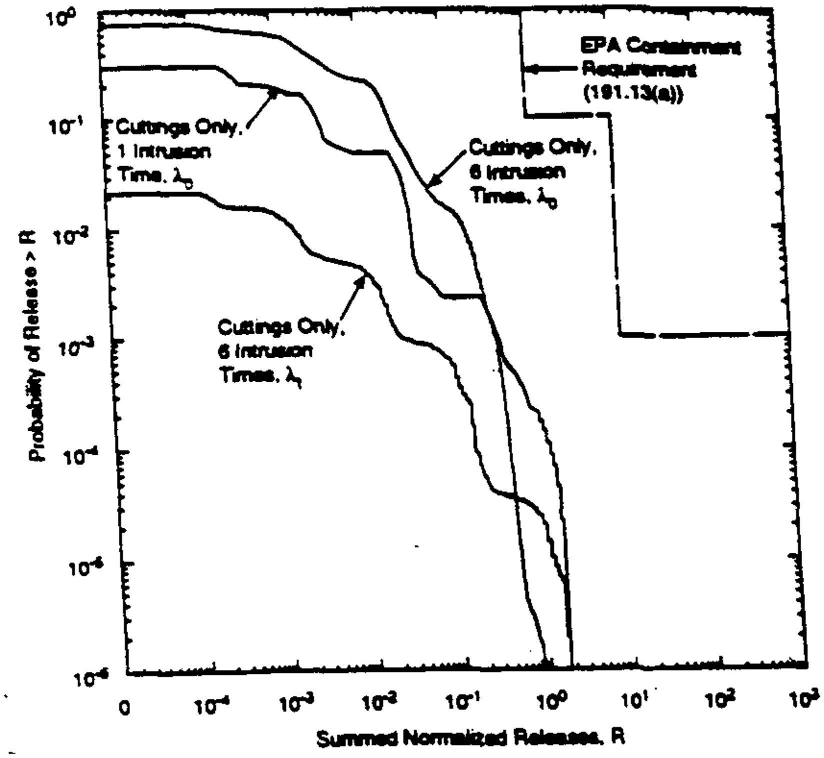


Figure 7-6. Mean CCDFs for Cuttings Releases Assuming Single and Multiple Intrusions for a Time-Independent (λ_o) Poisson Model and Multiple Intrusions for a Time-Dependent Model (PA, 1992, 1, Figures 5.1, 5.2).

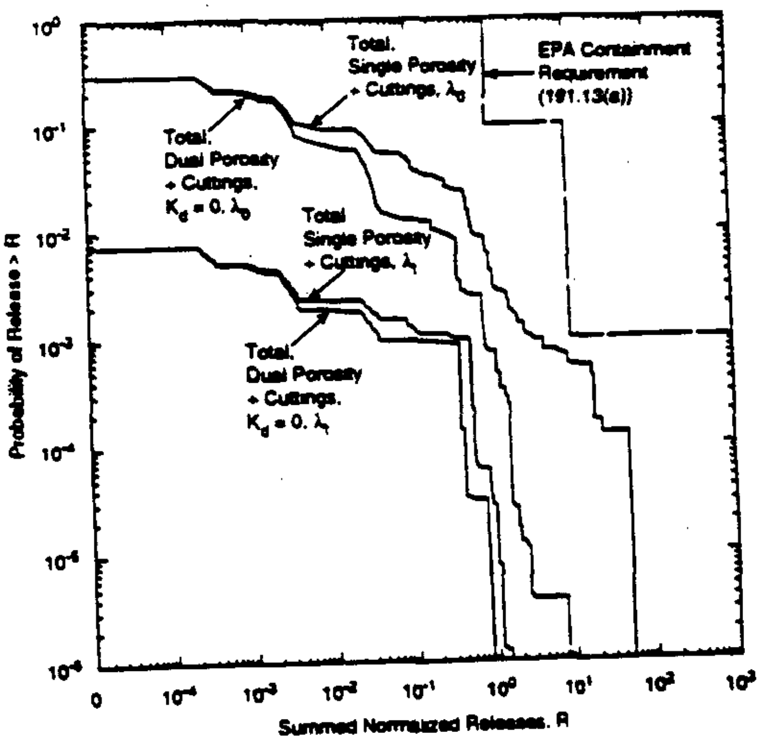


Figure 7-7. Comparison of Mean CCDFs for Total Releases from Intrusions Occurring at 1000 Years for Single Porosity and Dual Porosity Culebra Transport Models (PA, 1992, 1, Figure 5-4).

probabilities. Introduction of a time-dependent intrusion (λ_o) model has a profound effect on release reduction, nearly independent of type of the Culebra flow model. The addition of chemical retardation ($K_d \neq 0$) *results in summed releases nearly three or more orders of magnitude below the EPA limit* (**Figure 7-8**), lowermost CCDF); this conceptual model is believed to be the most realistic by the WIPP Performance Assessment Department (PA, 1992, 1, ch. 5). For the $K_d \neq 0$ model brine transport through the Culebra results in subsurface releases sufficiently lower than those at the surface so that the CCDF location is determined entirely by direct releases to the surface.

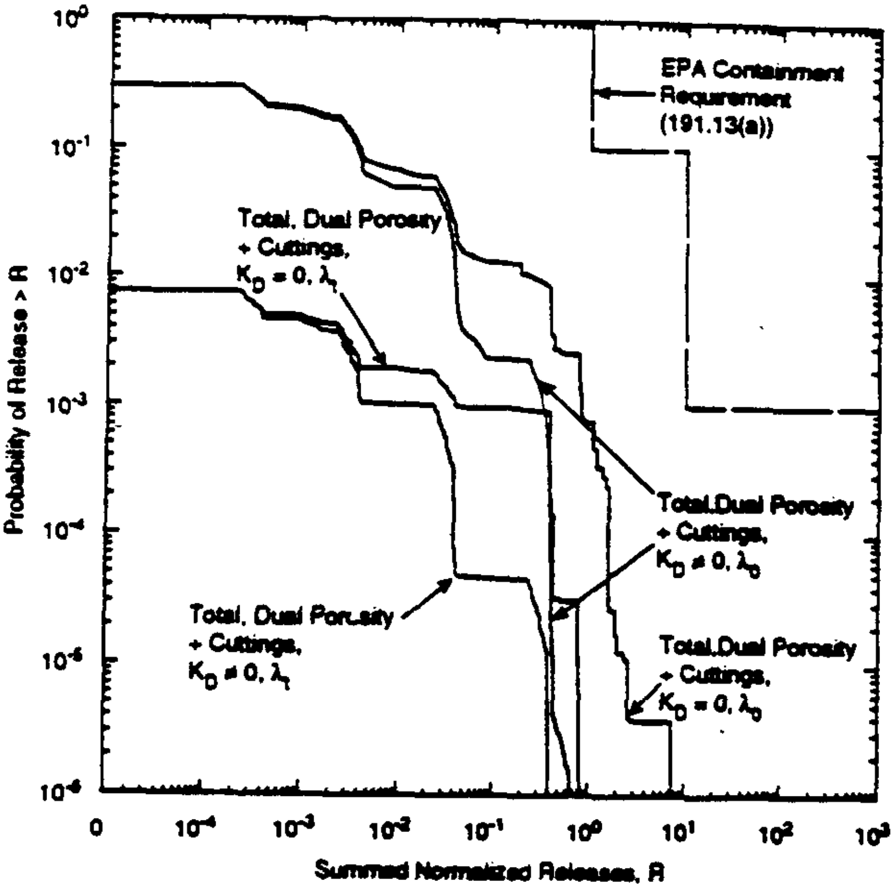


Figure 7-8. Comparison of Mean CCDFs for Total Releases from Intrusions Occurring at 1000 Years for $K_d = 0$ and $K_d \neq 0$ Dual Porosity Culebra Transport Models (PA, 1992, 1, Figure 5-5).

One final comment concerns borehole intrusion into a waste disposal panel in which a humid environment has dominated throughout its history and each room has encapsulated its waste contents, connected only by anhydrite layer B. For this model, the only releases to the accessible environment of any consequence would be through cuttings alone. The E1E2 scenario is eliminated, room contents rather than panel or repository contents form the source term, and subsurface flow pertains to scenario E1 alone. This conceptual model has not been considered by PA (Beauheim et al., 1993).

8.0 ISSUES AND RECOMMENDATIONS

In order to evaluate the technical adequacy of the WIPP Performance Assessment Program, identify any needed program changes, and make recommendations for carrying out these changes, the Performance Assessment Review Team performed a limited review of relevant PA and PA-related literature and the on-going performance assessment efforts. This review included discussions with appropriate WIPP Program staff and contractors. In performing its review, the PART has attempted to elucidate the specific issues associated with

- integrating the various types of information needed to justify and carry out the performance assessments that will provide the predicted quantitative results for comparison with the numerical compliance criteria of the regulations, and
- developing the reasonable expectation (or degree of certainty) through a process of documentation that provides the required assurance that this integration and these performance assessments are reliable and realistic and provide the right type of information on which to judge the efficacy of disposal.

Demonstrating that there is a "reasonable expectation of compliance" as required by the draft RCD (DOE, 1992) is one of the most difficult issues for the DOE, since, as implied by the various statements in the regulations, sole reliance on numerical predictions may not be appropriate because of the substantial uncertainties. These numerical predictions, as a result, require support based on the record of evidence, and they also require supplementation with qualitative professional judgments.

The difficulty in providing reasonable assurance has been recognized for some time. The Performance Assessment National Review Group (PANRG), in their review of performance assessments for high level radioactive waste disposal (Lieberman et al., 1985), observed that scientists, regulators, and decision makers have been thrust into unfamiliar territory because of the long time frame and large scale of the integrated, interdisciplinary effort. Such an effort is needed to select a site, develop a design, and conduct the experiments to identify and evaluate issues so that the disposal system protects the environmental quality and the health and safety of future generations. Also, as PANRG observed, the public now requires a level of professional documentation that has never been required before because of the magnitude of the real and perceived problems associated with nuclear waste disposal. As indicated by Ruckelshaus (1985), the major and controversial issues must be brought into the public and technical arena for open inspection, resolution, and consensus because "Risk management is not merely a set of techniques for arriving at correct answers. It must include communication to the public about how we arrive at environmental protection decisions. The values and assumptions that underlie all such decisions must be manifest. Transparency is the object of the whole process and public trust is the ultimate goal."

Early in the review effort, the PART realized that, because of the small number of review team members and their restricted technical breadth (e.g., no gas generation and geochemistry experts), it was not appropriate to perform only the limited technical review afforded by the time and budget. Various standing technical oversight groups are already in place (Subsection 1.2.7) and, through their continuing involvement with the WIPP effort, can provide a better in-depth evaluation of detailed technical issues. The PART believes that it is important to evaluate the process for developing (1) the base of supporting data and experimental evidence needed to perform the required compliance calculations, and (2) the adequate trail of documentation to provide the required "reasonable expectation of compliance."

This section presents a summary of the various issues identified by the PART review and the recommendations for addressing them. Subsection 8.1 discusses the overall issues and recommendations for improvements associated with the performance assessment process (e.g., identification and resolution of issues) and the development of an appropriate documentation trail to provide the required degree of certainty in PA results. Subsection 8.2 presents the major technical issues and uncertainties: first, those related to the natural system (Salado Formation, Rustler Formation, and Castile Formation); then, those that arise because the system is disturbed as a result of the waste and repository emplacement; and finally, those related to the engineered barrier systems that are important to the repository design. Subsection 8.3 discusses the scenario-related issues and recommended changes identified and developed by PART, and, finally, Subsection 8.4 summarizes the major PART findings and recommendations.

8.1 PERFORMANCE ASSESSMENT PROCESSES AND DOCUMENTATION

As discussed, the issues, assumptions, controversies, resolutions, and any other basis for judgments and decisions associated with siting and licensing must be well documented, since clarity and openness in this documentation trail are needed to build the required confidence in the PA on the part of decision makers. Since the actual PA document is the primary integrating document in this total PA documentation trail, the PART, in this subsection, examines and makes specific recommendations regarding PA documentation and the integration issue and also provides more general comments and recommendations regarding the total documentation trail.

In this subsection, the PA process is viewed very broadly and includes more than just the computer calculations required for comparison with the regulatory standards. The PA includes the various processes for determining what the issues are and how to resolve them: What calculations? What supporting, compliance-based, experimental evidence is required and how should it be obtained? What are the appropriate param measurements? What are the technical issues and which ones need to be resolved? What is the best method for resolving issues that are resolvable? The PART recognized that, because of the time frame of the test phase and the PA program at WIPP, it was just as important to examine the PA process for developing the required evidence as it was to sift through the existing trail of evidence in search of specific technical areas that need improvement. This realization was based on the reasoning that if the right process for developing the PA and preparing the associated documentation trail is in place, then the appropriate PA and documentation trail will be developed; whereas, if the process is wrong, then the PART recommendations will only be another set of review team mid-course correction recommendations for the WIPP PA team. As a result, this subsection also examines and makes recommendations regarding the PA processes for

- identifying and bringing major issues to the attention of the public and the scientific community,
- identifying unresolved issues and the needed compliance-based approach for resolving them, and
- documenting which issues have been resolved and how they were resolved.

8.1.1 Integration and Documentation

In the course of the PART's interviews with SNL and WID staff and during the PART's limited review of both the base level documentation (Subsection 1.4.3) and parts of the nearly twenty years of supporting technical record for WIPP, the team encountered cooperative and dedicated staff and generally solid, well documented technical work. However, there was no adequate framework for organizing and integrating all these very diverse details regarding various issues, assumptions, data, experiments, and preliminary calculations (which have been gathered and performed throughout the many years of investigation) into a logical, coherent, and digestible form. PART is not alone in this observation. EEG's second comment on the 1991 WIPP PA states: "We have mixed feelings about the organization of the Sandia reports (4 volumes of SAND 91-0893). The report appears quite logical, but it still requires much effort to gather all the information . . . ". As discussed in Subsection 3.2.1.1, the current PA (SAND92-0700/1-3, 1992) does not provide enough information on the assumptions, controversial issues, and the evolution of understanding that PART believes will be required for licensing. The current PA, for example, provides no coherent presentation of the plausible conceptual models for the supra-Salado hydrologic system, yet a coherent discussion of these plausible models is required in order to address the major interpretational issues discussed in Subsection 3.2.1.1 and to properly discuss and document the Culebra conceptual model and justify the various associated assumptions. Clear identification and documentation of conceptual model issues and assumptions, as well as the way that they were resolved and justified through laboratory and field measurements, other experimental evidence, expert panel findings, or numerical studies, is critical to the attainment of that quality of a reasonable expectation (or degree of certainty) required for compliance models. As a very minimum, the line of reasoning that integrates the available information and understanding in support of the current conceptual model needs to be outlined in the PA document.

During the PART review (Subsection 3.2.1.1) a variety of important past issues were identified (e.g., syndepositional versus post-depositional dissolution, rate of advance of dissolutioning and karst topography), which according to the chronology of the literature, had been resolved. However, the status and resolution of these issues were never discovered, and many of these important past issues are never alluded to in the current PA documents. The issue is not that these past issues have not been adequately resolved, but that there is less credibility when both the issue and its resolution or lack of resolution are not transparent. The PA documentation, being the primary vehicle for conveying the record of evidence to the decision makers, the regulators, and the public, must clearly identify and integrate a hierarchy of known issues, provide a brief synopsis of them, and briefly discuss their addressment status. The PA documentation must attempt to integrate these various issues by indicating, in an unbiased way, each issue's relative importance from a compliance-based perspective and provide a road map to the important literature (both favorable and unfavorable to the project's position). Discovery of this important knowledge should not be left to chance, since it detracts from the reader's confidence in the reported results. Furthermore, regulators and other decision makers should not be expected to perform the technical detective work (which the PART found necessary in many cases) to locate the appropriate supplementary material containing the detailed discussions needed to clarify these issues and assumptions, as well as to elucidate the controversies and the methods used to resolve them.

A related information integration issue identified by the PART during the course of their review, i.e., "corporate memory loss," was discussed with Dr. Wendell Weart, the SNL WIPP Project Manager. The "corporate memory loss" that occurs on long-lived projects like WIPP is the loss of the integrative knowledge, due to employee attrition, that relates all the specific investigations undertaken through time by the various principal investigators (PIs). While specific investigations may be well documented and the planning documents that have identified the needs for these specific investigations may exist, the knowledge that integrates this relationship and ties the results of these efforts to the problem or issue addressed, commonly is recorded only in the minds of project staff. W. Weart, who has been with the project since its inception, indicated that SNL is aware of this problem and is currently in the process of preparing a document to address the "corporate memory loss" issue. This document may provide the basis for developing an issue and assumption section that the PART believes should be an integral part of the WIPP PA.

The basic documentation issue identified here is nearly the same as the one that prompted WPIO's ongoing evaluation of the performance assessment params used in the WIPP PA: i.e., the data and params used in the WIPP PA must be of the appropriate quality and the requisite pedigree in order to avoid difficulties during regulatory review. For these very same reasons, it is important that the various issues (including any controversies) and assumptions important to WIPP be identified and the validity of their resolution be documented and tracked by a change control process to assure the same level of quality as is required for the params. This is because these issues and assumptions are as fundamental and controversial, and can have as great an impact on both predicted PA results and the demonstration of a "reasonable expectation of compliance." Some of the concerns and issues identified during the WPIO review of the PA params list may have become moot since the quality assurance procedures (QAP 2-3 for Param Selection) were put into place in November, 1992 (Rechard, Trauth, and Guzowski, 1992). Perhaps a similar approach (i.e., development of a QA procedure) would also be appropriate for the documentation and tracking of important issues and their resolution and the development of the associated pedigree for this important information (i.e., tracking issue origin and the continuing refinement in definition and the method of addressment through time).

A more specific documentation issue identified by the PART is related to the way that confidence in the actual compliance models and the assumptions needed to support these compliance models is developed. The PART, for example, performed many hand calculations in order to check the reasonableness of assumptions and believes that they provide a simple means for establishing confidence and should be presented in the PA when appropriate. The PART observed that, in general, the PA documents present only a brief description of the actual compliance models and that there is no confidence-building description of the progression of simple deterministic or stochastic modeling that is typically investigated as part of the process of examining and justifying the various conceptual model assumptions. There is no description of the progression of modeling analysis that must have been performed to demonstrate that the appropriate level of modeling had been selected for compliance analysis. This last step is especially important when it appears to leave out important processes (see Subsection 5.1.5). The PART believes that this progression needs to be clearly documented in the PA.

Another specific documentation issue relates to compliance-based assessment. Since every outstanding issue cannot and need not be resolved to demonstrate compliance, it is important for the PA document to indicate clearly what must be known and resolved in order to reach compliance and at least to outline the reasoning (and/or present calculations or experimental evidence) that supports this assessment.

PART Recommendations: PA documentation must be considered to be the primary integrating document and, as such, the PA document should contain an evolutionary summary (e.g., similar to the type found in SAND89-0462, 1989) of the major resolved and unresolved issues, discuss their relevance to compliance analysis, and provide a guide to the literature (e.g., issue resolution documents, as discussed below) that describes each issue in detail. Perhaps the document discussed by Weart, see above, could serve as a basis for this section.

The PA must provide a clearer documentation of the line of reasoning that integrates available information and understanding in support of the current compliance conceptual models and indicate why only a certain level of (compliance-based) knowledge is needed. Interpretational and param scale (i.e., both spatial and temporal) issues need to be specifically addressed.

The PA document should present hand calculations, when appropriate, and at least a brief documentation of the progression from the simpler modeling efforts used to justify assumptions and to help achieve those qualities of "reasonable degree of certainty" and "reasonable expectation." It is also important for the PA to justify and document the analyses that led to the model selected for compliance.

As will be discussed in the next subsection, there is a need for a specific PA process for issue identification, resolution, and documentation. A format and style for these issue resolution documents needs to be prepared, and the past issues that have been identified in the "corporate memory loss" must be documented in this format. These issue resolution documents need to identify and define each issue; identify and summarize the chronology of literature, workshops, and important meetings; summarize the method of resolution; and document the consensus and any dissent. These documents should probably be prepared under strict QA with appropriate documented external review by qualified experts.

8.1.2 Performance Assessment Process

As discussed earlier, the "PA process" in the context of these discussions should be viewed very broadly and includes, for example, the various processes for determining and resolving issues and deciding what to measure and calculate. The PART has determined that there is no formal PA process or mechanism for dealing with issues (i.e., their identification, evaluation, resolution, and documentation) within the WIPP PA program. In this regard an important area of concern identified by the PART is related to the flow of information among the DOE, the PA staff, the PIs, and other participants, in order to identify problems and issues and to develop means for their resolution. From the PART review it is not clear how DOE management, PA personnel, and PIs work together to determine and fund the modeling and experimental approaches and to insure that these efforts are compliance-based, so that the experiments will lead to data of the appropriate spatial and temporal scales for compliance PA. Questions of concern include the following:

- How does the ongoing PI modeling eventually integrate with PA modeling and how is this planned?
- Is the information flow between PIs and the PA team, especially across contractors, as smooth as it could be?
- What is the process for, and who is involved in, identifying where there is sufficient scientific understanding and data and where there is not?
- How is it determined which scientific issues are resolvable by further data gathering or experimentation and which ones cannot be so resolved?
- What is the process for reevaluating the repository design to determine if difficult or unresolvable critical issues can be resolved by design changes that avoid the need for addressing them?
- Are estimates for compliance-driven data gathering and experimentation realistic in terms of what can actually be achieved (i.e., Can science actually deliver and are the time frame and costs realistic?) and how is this determined?
- Is there a process for evaluating proposed programs to determine if they are realistic and likely to lead to the desired closure of issues relative to data and understanding?
- How are decisions made about what gets modeled and when, and what gets measured and when?
- Is there a process for weighing the various programs for resolving technical issues against each other to determine what gets funded and when?

The PART believes that the WIPP PA program needs a formal documented method for dealing with the identification/tracking/resolution of WIPP PA issues. One example that illustrates this point arose during the PART discussions with EEG regarding the issue of the cuttings scenarios (Subsection 3.2.1). The PART was unable to determine whether the scenario identification and selection process would ever be revisited or what parties and types of concerns would cause it to be revisited. Another example that illustrates the need for a formal issues identification and resolution process (Subsection 3.2.1.2) relates to the oil and gas resource potential in the WIPP area and concerns raised by EEG regarding potash mining and drilling frequencies. The PART believes that there is a need to re-examine the natural resource issue as raised in §191.14 (e) in order for DOE to determine and clearly state its position regarding the oil/gas and potash resources in the vicinity of WIPP. The PART can make a recommendation, but what process is in place to allow the concerns of other parties to be raised and subsequently evaluated, addressed and documented?

The formal documented method for dealing with WIPP PA issues must provide ways for identifying issues, evaluating them, making a decision on the approach for their resolution, tracking their eventual resolution, and documenting the whole process. The approach must provide a method in which to present issues for subsequent evaluation and consideration for addressment. An approach and decision methodology to guide this evaluation will be needed so that newly identified issues can be evaluated and either (1) the issue is closed, once the reasoning for closure is formally identified and documented, or (2) the issue is moved forward and given a refined definition to serve as the basis for development of an approach for addressment.

Once an issue has been identified and moved forward for addressment, the issue identification/tracking/resolution process must provide a number of things.

- A means for the issues to be clearly identified and defined.
- A mechanism for each issue to be evaluated in terms of its relative importance to compliance analysis (including an evaluation of the effects of not resolving the issue).
- A mechanism for determining whether an issue can be resolved and, if it can, how it can be resolved. All the plausible alternatives (including engineering approaches to alternative design that avoids the issue) should be identified, along with complete time, cost, and probability of success estimates. This mechanism should first determine if the addressment of the issue is what Weinberg (1985) would describe as *"trans-scientific "* or beyond the power of science to answer. It is important to realize that not every issue need or can be addressed. It is also important to separate the questions that are beyond our current ability to address and those that are beyond our means in terms of time or cost.
- A means to classify and rank the various issues so they can all be put into the proper perspective for the decision makers for prioritization and allocation of resources.
- A means to track the issue and its eventual resolution.

PART Recommendation: In order to achieve those qualitative qualities of "reasonable degree of certainty" and "reasonable expectation," there is a need to document these issues and their status of resolution through a series of issue resolution documents to aid both the licensing reviewers and any other interested parties (Subsection 4.2.1.1). The PA should contain a brief summary of the major resolved and unresolved issues and provide a reference to these issue resolution documents, and these documents should be prepared under strict QA with appropriate documented external review by qualified experts.

8.1.3 Repository Design/Facility Configuration Control

Another important area identified by the PART is related to repository design. The original WIPP repository design and repository level were established before the current regulations were promulgated and before much of the in situ testing and measurements were completed. In their cursory review of the design, the PART identified the following issues and concerns:

- Are the repository design and repository level fixed and why?
- If the repository design is not fixed, how has the repository design changed in response to information from the site characterization and PA activities?
- Who is in charge of design configuration control to insure that design changes are compatible with other components of repository operation and performance?
- Is there a formal process and procedure for revisiting the design to determine if it must be updated in response to improved understanding of the subsurface and the waste disposal system?

PART Recommendations: Prepare a document containing the history of the design process and record (or develop) the procedures that govern the design change control concerns discussed above.

8.2 REPOSITORY SYSTEM UNCERTAINTIES

In addition to the general issues of process and information referenced above, PART has identified other important technical and management issues to be resolved. The significance of these issues cannot be properly assessed until a complete system model of WIPP is available. The issues associated with the natural system are presented first, followed by a discussion of repository-related issues, and finally, those related to future events and processes.

8.2.1 Salado Formation

Uncertainty appears to center around far-field pore pressure and permeability of impure salt, relatively pure salt, and interbeds in this heterogeneous unit. Particularly unsettling are questions concerning hydraulic (and possibly chemical) equilibrium of the system. Pore pressures in the very low permeability salt are expected to be near lithostatic (15 MPa) and in equilibrium with those of the interbeds (12.5 MPa), but the highest pore pressure measured in the halite is 9.5 MPa. Careful investigations of the physical properties and chemical equilibria of pressurized core from "representative" halite members of the Salado Formation obtained from the repository horizon may provide fundamental information toward a solution to this problem and to that of whether or not Darcy flow occurs in the undisturbed salt. More important, however, is a thorough characterization of flow properties of the heterogeneous interbeds.

PART Recommendation: Obtain pressurized core from representative pure and impure halite and interbeds of the Salado Formation at the repository horizon in the far-field for laboratory assessments of flow properties and processes.

8.2.2 Rustler Formation

Most recent work on the Rustler Formation has focused on mechanisms of contaminated brine transport through the Culebra dolomite following inadvertent borehole intrusion into and through waste panels. Apparently, these important investigations are being carried out to the exclusion of considerations of flow along other potential transmissive pathways in the Rustler, such as the Rustler-Salado contact. Three specific models for brine flow through the Culebra have been employed in consequence modeling to date. However, as shown by studies of cores obtained near walls of a shaft, the Culebra is so heterogeneous, on the scale of ms, that results of the models may well be misleading. Field tracer tests are essential for understanding flow and transport through this unit, and perhaps others in the Rustler Formation, unless they can be excluded on other grounds as potential migration pathways. A better understanding of potentiometric surfaces associated with various units of the Rustler Formation may be important. Finally, there is a need to carry out the column radionuclide sorption test on the cores removed from the air intake shaft (Subsection 4.3.3.4 and Figure 4-9).

***PART Recommendation*:** Continue column radionuclide sorption testing and conduct field tracer tests to determine large-scale flow properties of the Culebra dolomite.

8.2.3 Castile Formation

Continuing characterization of the nature and physical properties of the Castile anhydrites and potential oil-bearing strata below is important only for purposes of inadvertent human intrusion scenarios. It appears now as if the Castile pressurized brine pockets, conservatively estimated to underlie approximately 40% of the WIPP repository, have been isolated from each other and from recharge for a very long time. If so, restricted volumes of brine are available for contaminant transport to the surface and through the subsurface, should one or more of these pockets be penetrated.

PART Recommendation: Continue geophysical studies, using remote sensing methods, in an effort to define better the extent of the pockets and volumes of brine associated with them.

8.2.4 Impact of the Repository and Waste Emplacement

Excavation of the repository perturbs the thermal, chemical, hydrologic and mechanical fields of the Salado Formation. The most profound effects are to be found in the immediate vicinity of the opening and are manifested by formation of the disturbed rock zone (DRZ). Microfracturing and faulting associated with high stresses and rapid transient creep closure lead to reduced pore pressure and greatly enhanced permeabilities. Brine inflow rates are high initially, falling off to steady-state rates as intergranular water is drained from the DRZ. Although it is not yet fully characterized, the DRZ is pervasive from excavation surfaces to about 3 ms (9.8 feet) into the salt, where it grades into a zone of diminished pore pressure but low permeability. Apparently, new DRZ may be created with time during creep closure. Eventually, closure slows and ceases and the DRZ is expected to self-heal when stress gradients are reduced by back-pressure.

Strongly coupled with closure rates, the nature and extent of the DRZ, and the rates of brine inflow, are rates of generation of gas from biodegradation, corrosion, and radiolysis of the emplaced transuranic waste. The quantity of gas generated depends markedly on the quantity of brine available, and gas pressures depend on the volume of pore space available for storage. Within waste disposal rooms, the pore space available for gas storage diminishes with time during closure so that gas pressure increases at a rate determined by gas-generating mechanisms, permeabilities to gas, and gas storage space available beyond disposal room walls. The DRZ not only provides some of the storage space required but, more important, provides the primary link between the waste disposal room and the remainder of the repository. It appears now, from preliminary analysis of fully coupled three-phase (salt, brine, gas) models, that variable gas-generation rates (dominantly humid environment) are most reasonable and that disposal room volume-pressure history may depend primarily on gas storage and transport in adjacent interbeds. With ongoing improvement in critical param characterization, fully-coupled three-phase fluid modeling will surely provide the best representations of disposal room dynamics and fluid flow for performance assessment.

Gas generation studies are ongoing; laboratory studies are expected to be augmented by the bin and alcove tests within the repository upon implementation of the Test Phase Plan. Brine inflow rates continue to be monitored with improved measurement techniques. One key area that requires more intensive investigation is the microstructural nature and extent of the DRZ, its physical and mechanical properties, and its time-dependent behavior. Detailed microstructural studies of cores through the DRZ combined with field and laboratory tests would characterize the micromechanical processes responsible for pore and grain boundary damage. Simultaneously, experimental investigations of micromechanical processes giving rise to the transient mechanical response (in the dilatant field) could be carried out under simulated repository conditions (e.g., humid, gas-pressurized). Together, these investigations would surely lead to a much more thorough characterization of the DRZ, its transition into the depressurized zone, and its time-dependent behavior, including conditions required for self-healing.

Finally, implementation of the Munson-Dawson model, modified to include a damage factor, is essential for realistic approximation of disposal room closure that includes transient creep and associated pore and grain boundary damage. The current elastic-steady state model, that matches measured closure rates by reducing elastic moduli, fails to account for flow in the transient creep regime during which the DRZ is created. The premise upon which the current model is based is physically unreasonable; the PA department is fully aware of this and is in the process of incorporating the much more complex modified M-D model.

***PART Recommendation*:** Conduct detailed studies of the nature and extent of the DRZ by means of microstructural analyses and by laboratory and field measurements of physical properties. Carry out a systematic experimental and micromechanical study of the time-dependent behavior of Salado salt deforming in the transient creep regime, in the dilatant field, under simulated repository conditions. Complete incorporation of the M-D model and use the model in coupled three-phase studies.

8.2.5 Engineered Barriers

The four shafts are the most likely pathways for the transport of mixed waste to the accessible environment under undisturbed (no human intrusion) conditions. The strategy for sealing the shafts is to maximize the amount of consolidated, low permeable salt in the shaft between the top of the Salado Formation and the repository level. Creep closure of the shaft opening is expected to consolidate the crushed salt in the lower portion of the shafts to near-intact (95%) density within 100 years after emplacement. Composite seals will be located above and below the crushed salt seals to prevent brine from saturating the crushed salt and inhibiting consolidation.

The upper shaft seal system in the Rustler Formation will be comprised of a sequence of water bearing seals made up of bentonite clay segments confined by adjacent concrete bulkheads. The purpose of the seals is to limit groundwater flow from the formation into the lower portions of the shaft during the consolidation phase of the crushed salt seals. The brine inflow rate must be reduced from 1000 m^3/year to 1 m^3/year in order for the lower 100 m (328 feet) of the shaft seal to reach 95% fractional density in 100 years. The DRZ in the rock surrounding the shafts may be removed or sealed with grout to prevent groundwater from flowing around the plugs and into the underlying crushed salt seals.

The panel and drift seals are designed to inhibit long-term migration of radionuclide-contaminated brine through the drifts to the base of the shafts and to isolate radionuclides during the operational phase of the repository. The seals are similar to the shaft seals and comprise both long-term and short-term seals. The panel entryway seals are intended to return intervals within the repository to hydraulic properties similar to the intrinsic conditions in the undisturbed host rock salt and provide substantial resistance to flow through the repository, as well as to separate volumes of waste from one another and from the shafts. The time for consolidation of the crushed salt portion of the seals is similar to that for the lower shaft seals, approximately 100 years after installation.

The DRZ in the salt surrounding the seal locations is expected to heal eventually after the crushed salt reaches 95% fractional density and resists further creep closure of the opening. The damage zone around the concrete bulkheads is expected to heal much earlier, due to the back stresses that will be generated. The fracture system in MB 139 below the excavations appears to be extensive and possibly interconnected. Unlike the disturbed zone in the halite rock mass, the fractures in the interbeds are not expected to heal. Many of the fractures are thought to have existed prior to excavation. The existence of pre-excavation fractures suggests that, even if the fractures close as the local stresses return to lithostatic conditions, they are unlikely to "heal" and are therefore likely pathways for pressurized gas and brine transport. One option under consideration is the use of cement or crushed salt grouts to seal the interbeds, particularly around the panel seal locations. Effective grouting may be difficult to achieve because of difficulties in delivering the grout to the fracture system and the possibility of deformation of the interbed as the rooms close and the surrounding rock mass dilates.

An additional pathway to anhydrite layer B is expected through the rock bolt holes that intersect the overlying interbeds. Therefore, the pathways for contaminant migration are likely to change during the first several hundred years after disposal. Immediately after closure, gas and brine will be able to flow through the DRZ into MB 139 and anhydrite B. As the DRZ heals, gas and brine movement will be limited to anhydrite B. Because the storage and thickness of MB 139 are expected to be significantly greater than those of anhydrite B, the extent and pressure of any gas or brine in the interbeds will depend in part on the time MB 139 is hydraulically (pneumatically) connected to the waste panels.

None of the conceptual models describing shaft and drift seal behavior has been incorporated into the performance assessment analyses for preliminary comparison with 40 CFR 191 or 40 CFR 268.6. This is one of the most serious deficiencies in the performance assessment program identified by this review. The primary reason given by SNL for not including engineered barriers is related to budget constraints and the need to address other aspects of the repository system that were assigned a higher priority. The importance of engineered barriers is now recognized by the scientific and management staff supporting WIPP, and these features will be incorporated in subsequent performance assessment analyses.

***PART Recommendation*:** In situ tests are planned to measure the characteristics and behavior of the fractured interbeds, which should improve understanding of the potential for and extent of contaminant transport. In addition to these studies, a large-scale field test should be considered to provide empirical information on the healing of the DRZ in the halite and polyhalite host rock. This might involve a rigid bulkhead in the experimental area of the WIPP facility. After characterizing the DRZ in the salt and interbeds, a bulkhead would be installed in the opening and changes in the DRZ properties monitored. The bulkhead would simulate DRZ healing after the room closure is complete and the stress state returns to lithostatic conditions. The empirical data from such an experiment would likely improve the confidence in our understanding of the short-term behavior of the DRZ and its effect on other components and processes (e.g., brine inflow). Experiments should continue on crushed salt reconsolidation behavior under low pressure and pore fluid conditions up to saturation.

The significance of the above issues and the adequacy of the tests planned are difficult to assess until the seal systems are incorporated in the system model for WIPP. While the subsystem models provide useful insight into the sensitivity of the seal performance to local conditions it is not possible to identify and prioritize additional studies without knowing the contribution of the various features and processes to system performance. At a minimum, simplified representations of the shaft and panel entryway seals, DRZ, and interbeds should be incorporated in the system model in the next performance assessment iteration to determine the sensitivity of the repository performance to the params and processes involved. Until this is done, it is not possible to assess whether the WIPP is likely to meet the regulatory compliance standards.

8.3 SCENARIOS

8.3.1 Undisturbed Repository Scenarios

Numerical two-dimensional modeling of the base-case (undisturbed) scenario has concentrated on providing evaluations of the most sensitive params affecting repository behavior with no attempt to demonstrate compliance with the regulations. Gas and brine migration laterally through interbeds and vertically through shaft seals has been the primary focus of the simplified models to date. Three of the models do not permit adjustment of void volume; the fourth simulates closure by estimating the reduction, with closure pressure and time, of void space in a disposal room. In the models including the DRZ, fixed porosity and permeability are assigned; no provision is made for time-dependent healing or additional fracturing of interbeds that may result from increased gas pressure. These models do not include representation of proposed engineered barriers but rather evaluate lengths and permeabilities required of the barriers (ignoring the DRZ) to become effective seals. The principal results are (1) lateral gas release is very limited and vertical release, to the Culebra, is unlikely provided that the lower shaft seal has a permeability less than 10^{-19}m^2 ; and (2) brine that has been in contact with waste has not migrated beyond the DRZ in 10,000 years.

PART Recommendation: Replace the current elastic-steady-state model for excavation closure with the modified M-D model to obtain more realistic closure models that include transient creep and associated pore and grain boundary damage. Implement fully-coupled, three-phase (gas, brine, salt) flow in base-case scenario using brine and gas properties, reasonable inflow and generation rates, and nonlinear equivalent viscosities estimated from the M-D model of Salado salt flow. Incorporate in these models time-dependent behavior of the DRZ and of engineered barriers.

8.3.2 Disturbed Repository Scenarios

Inadvertent and intermittent human intrusion by exploratory drilling for resources has been demonstrated to be the only event likely to release radionuclides in concentrations near regulatory limits. Of the fifteen possible combinations of four types of intrusion events, only three have been modeled to date along with the base-case (undisturbed) scenario. These three summary scenarios include (1) drilling through a waste-filled panel and into a pressurized brine pocket below (E1); (2)

drilling into a waste panel (E2); and (3) both types of drilling events occurring in the same panel (E1E2). From four to ten such inadvertent intrusion events may occur at WIPP in 10,000 years. For each type of event, contaminated particulate matter and brine reach the wellhead in the drilling fluid (direct), whereupon the hole is plugged and further flow (indirect) of contaminated brine to the accessible environment is assumed to be through the Culebra dolomite.

Probabilities and consequences of total direct and indirect releases to the accessible environment for intrusions taking place at 1,000 years have been calculated for comparison with the EPA containment requirement. Probability-consequence curves, whose locations are shown relative to the EPA limit, depend primarily upon the number and type of intrusions and direct releases and the type of brine transport through the Culebra dolomite. For the most conservative combination of those processes modeled, releases still fall below the EPA limit. Some of the assumptions employed in this E1E2 scenario, in which indirect releases dominate, are physically unreasonable; certainly in this category are plug placement contrived to maximize releases and the 10,000-year integrity of intact borehole plugs. Of the conceptual models considered to date, those regarded as most realistic by the Performance Assessment Department yield releases more than two orders of magnitude below the EPA limit. This model, also E1E2, assumes time-dependent intrusions, direct releases, and indirect releases by subsurface flow through the Culebra with $K_d \neq 0$. Still smaller releases may be realized from the humid, isolated-room scenario (E1E2 is eliminated) which requires no artificial restraints; this scenario has not yet been modeled.

PART Recommendation: Replace the E1E2 scenario currently modeled with a similar one that permits variable placement and normal degradation of plugs. Both time and sequence of borehole penetrations will then become important factors in consequence modeling and releases estimated will be much more realistic.

8.4 PERFORMANCE ASSESSMENT INDICATORS

The WIPP Performance Assessment Department at SNL has developed a comprehensive and technically sound PA methodology. The underlying philosophy of the SNL approach appears to be the development of increasingly more realistic (complex) models which require increasingly more specialized and precise data. Because of the level of modeling involved, this complex system has not been fully developed and implemented. For example, this modeling effort does not take into account coupled responses which will certainly occur in the repository.

Although SNL has expended considerable effort in the development of these detailed models, they have not demonstrated or documented why this approach is necessary to reach a compliance decision. In short, the approach being utilized by SNL may not be compatible with compliance-based performance assessments.

Considerable effort has been focused on modeling of natural barriers, significantly less effort has been concentrated on engineered barriers. Since compliance with the regulations cannot be achieved solely on the basis of the use of natural barriers, a complete program needs to be undertaken to develop models that include the performance of engineered barriers. In addition, seal performance will be an important consideration for compliance with 40 CFR 268.6.

Finally, component sensitivity analyses utilizing these complex, yet incomplete models may lead to incorrect conclusions that affect programmatic decisions and compliance activities.

PART Recommendation: In order to develop a compliance-based approach to performance assessment, it is essential that WIPP develop a system model for the repository which includes engineered as well as natural barriers. In addition, consideration should be given to the development of simplified models to provide direction for a compliance-based performance assessment program. These simplified models reduce the complexities in dealing with coupled effects and are generally very reliable when the params fall within a limited range.

8.4 CONCLUSION

All individuals contacted by the PART, recognized as experts in their respective disciplines, displayed the highest level of professionalism in this state-of-the-science WIPP effort. Although the review teams has made suggestions on means of improving selected areas of the performance assessment activities, the overall program clearly has a solid foundation.

In recapping major recommendations, technical issues requiring further investigation and incorporation into system models include: far-field hydraulic properties of Salado formation interbeds and halite and those of Rustler formation transmissive members; the transient creep behavior of the Salado salt and character, extent and behavior of the DRZ during creep closure; performance of engineered barriers together with the natural system in limiting fluid migration from the fully coupled disposal system; and implementation of complete system models simulating releases for both undisturbed scenarios and physically reasonable disturbed scenarios that have resulted from inadvertent human intrusion. Programmatic decisions based on incomplete system analyses can lead to incorrect decisions and allocation of resources.

Documentation of PA activities, while comprehensive for short periods, must be related summarily to the evolution of the entire WIPP project in order to make it easier for individuals, teams and agencies to track issue resolution status. The success of all integrated test programs and the entire performance assessment effort for WIPP will be determined by the final product — a compliance determination.

APPENDIX A

Applicable Review Criteria

The Performance Assessment Review Team (PART) identified a subset of the criteria contained in the *Regulatory Criteria Document for the Disposal of Defense Transuranic Mixed Waste in a Geologic Repository*, Rev. 0 (RCD), as a partial basis for the evaluation of the WIPP performance assessment (PA). Listed below are the generic criteria from the RCD and specific criteria developed by the PART for application to the WIPP PA program. Tables A-1 through A–4 contain the PART comments on each criterion.

1.0 GENERAL COMPLIANCE CRITERIA

RC1.001 RCD CRITERION:

The DOE shall apply the following criteria in determining compliance with applicable portions of 191, 264, and 268 that apply to the disposal of defense-generated TRU radioactive waste, during the disposal, closure, and post-closure phases of the repository.

PC1.001 PART CRITERION:

The PART reviewed the following criteria to establish if WIPP will comply with the applicable portions of 40 CFR 191, 264, and 268 with regard to performance assessment.

RC1.002 RCD CRITERION:

Releases of concentrations of hazardous constituents and cumulative releases of radionuclides shall be demonstrated not to exceed the quantitative limits in 40 CFR 191.13(a), 191.15, 191.16, and the health-based limits or other acceptable criteria, established pursuant to 264.601 and 268.6(a), with a reasonable expectation of compliance.

PC1.002(A) PART CRITERION:

The PA modeling activities utilize the quantitative radionuclide release limits of 40 CFR 191.13(a), 191.15, and 191.16 for the determination of compliance to 40 CFR 191.

PC1.002(B) PART CRITERION:

The PA activities utilize the health-based limits, established pursuant to 264.601 and 268.6(a) for the determination of compliance with RCRA.

RC1.003 RCD CRITERION:

The demonstration shall predict releases from all pathways, including groundwater, surface water, soil, and air, at the boundary of the controlled area of the repository, which shall be equivalent to the boundary of the lateral extent of the unit boundary established for the RCRA.

PC1.003(A) PART CRITERION:

The PA modeling addresses releases from all pathways, including groundwater, surface water, soil, and air, at the boundary of the control area of the repository.

PC1.003(B) PART CRITERION:

The boundary of the control area of the repository is equivalent to the lateral extent of the unit boundary established for RCRA.

RC1.004 RCD CRITERION:

Compliance of the disposal system performance with 191.13, 264.601, and 268.6 shall be evaluated by performing predictions of contaminant migration (using quantitative computational models and qualitative analysis) that are supported by laboratory and field investigations as well as by expert judgment.

PC1.004 PART CRITERION:

The qualitative computational model and the quantitative analysis for disposal system performance are supported by laboratory and field studies, as well as expert judgments.

RC1.005 RCD CRITERION:

The basis for demonstrating that the geologic disposal system complies with 191.13, 264.601, and 268.6 shall be documented.

PC1.005 PART CRITERION:

The SNL PA and the WID compliance staffs are documenting the basis for demonstrating that the geologic disposal system complies with 191.13, 264.601, and 268.6.

RC1.006 RCD CRITERION:

The record(s) shall include the quantitative and qualitative evidence that was used to develop the performance assessment models as well as supplementary information (e.g., natural analogues, evidence that supports the process models, parameter ranges, geometric conceptual model(s), hypotheses, and simplifying assumptions used).

PC1.006 PART CRITERION:

The records include the quantitative and qualitative evidence that was used to develop the performance assessment models as well as supplementary information (e.g., natural analogues, evidence that supports the process models, parameter ranges, geometric conceptual model(s), hypotheses, and simplifying assumptions used).

RC1.007 RCD CRITERION:

New information relevant to the performance of the disposal system shall be incorporated in the compliance analysis and the assessment of compliance will be reevaluated until the repository is closed.

PC1.007 PART CRITERION:

The SNL PA and WID compliance staffs are incorporating new information relevant to the performance of the disposal system in the compliance analysis.

RC1.008 RCD CRITERION:

Performance of the disposal system shall be evaluated based on the projected contributions of both natural and engineered barriers. It shall be demonstrated that the system controls, minimizes, or eliminates releases.

PC1.008(A) PART CRITERION:

Performance of the disposal system is being evaluated based on the projected contributions of both natural and engineered barriers.

PC1.008(B) PART CRITERION:

It is being demonstrated that the barrier system controls, minimizes, or eliminates releases.

RC1.009 RCD CRITERION:

All components of the geologic disposal system, including the characteristics and radionuclide content of the emplaced waste, shall be considered when predicting the system performance unless it can be demonstrated that a component makes a negligible contribution to the overall system performance.

PC1.009(A) PART CRITERION:

All components of the geologic disposal system, including the characteristics and radionuclide content of the emplaced waste, are considered when predicting the system performance.

PC1.009(B) PART CRITERION:

Components which make a negligible contribution to the overall system performance are not considered.

N

Pathways for Migration

RC1.010 RCD CRITERION:

In demonstrating compliance with the environmental performance standards, potential pathways for the migration of radionuclides and hazardous constituents shall be identified and evaluated. All potential pathways shall be considered, including groundwater, surface water, soil, and air.

PC1.003(A) PART CRITERION:

The PA modeling addresses releases from all pathways, including groundwater, surface water, soil, and air, at the boundary of the control area of the repository.

RC1.011 RCD CRITERION:

The pathways evaluated shall be consistent for analyses performed to demonstrate compliance with the environmental performance standard of 264.601, the no-migration standard of 268.6, the containment requirements of 191.13, and the individual protection requirements of 191.15.

PC1.011 PART CRITERION:

The pathways evaluated by SNL for the analysis to the containment requirements of 191.13 and the individual protection requirements of 191.15 are consistent with the pathways evaluated by WID for demonstrating compliance with the environmental performance standard of 264.601 and the no-migration standard of 268.6.

RC1.012 RCD CRITERION:

The compliance analyses shall consider the likelihood and consequences of events and processes that may disturb the disposal system (specifically including earthquakes, floods, severe storm events, droughts, or other natural phenomena).

PC1.012 PART CRITERION:

The compliance analyses consider the likelihood and consequences of events and processes that may disturb the disposal system, including earthquakes, floods, severe storm events, droughts, and other natural phenomena.

RC1.013 RCD CRITERION:

The compliance analyses need not consider processes and events that are estimated to have less than 1 chance in 10,000 of occurring over 10,000 years. For events and processes with a probability of greater than 1 chance in 10,000 over 10,000 years, an evaluation shall be made of the potential impacts and consequences together with an evaluation of the ability of the disposal system to isolate wastes if the event or process occurs.

PC1.013(A) PART CRITERION:

The PA staff developed a process to consider many potential processes and events.

PC1.013(B) PART CRITERION:

A process assigns a probability to each process or event.

PC1.013(C) PART CRITERION:

Processes or events with likelihood of less than 1 chance in 10,000 over 10,000 years are removed from further consideration.

PC1.013(D) PART CRITERION:

For remaining processes or events, an evaluation of the ability of the disposal system to isolated wastes if the event or process occurs is being conducted.

PC1.013(E) PART CRITERION:

The consequences of the occurrence of the process or event are evaluated.

RC1.014 RCD CRITERION:

A reasonable expectation that natural processes and events shall not result in a release of radionuclides or hazardous constituents in excess of applicable standards shall be demonstrated.

PC1.014(A) RCD CRITERION:

Natural processes and events are being analyzed as part of the performance assessment.

PC1.014(B) PART CRITERION:

It is being demonstrated with reasonable expectation that natural processes and events do not result in a release of radionuclides or hazardous constituents in excess of applicable standards.

RC1.015 RCD CRITERION:

The likelihood of inadvertent human intrusion shall be evaluated, considering that controls will be imposed to make such intrusions unlikely. The judgment of the likelihood of human intrusion shall be based primarily on an evaluation of the expected effectiveness of permanent markers.

PC1.015(A) PART CRITERION:

Consideration is given to controls that will be imposed to make human intrusion unlikely.

PC1.015(B) PART CRITERION:

An evaluation of the effectiveness of permanent markers is being conducted.

PC1.015(C) PART CRITERION:

The judgment of the likelihood of human intrusion is based primarily on the evaluation stated in PC1-015(b).

PC1.015(D) PART CRITERION:

The likelihood of human intrusion is being evaluated.

RC1.016 RCD CRITERION:

The consequences of human intrusion events shall be evaluated and included in the record. Human intrusion events shall be no more severe than inadvertent and intermittent intrusion by exploratory drilling for resources (other than any resources provided by the disposal system itself). Each intrusion will be assumed to be an isolated occurrence, such that a particular intruder will inadvertently intrude only once. The assessments shall assume that systematic or persistent exploitation within the controlled area will not occur.

PC1.016(A) PART CRITERION:

Human intrusion events are considered to be no more severe than inadvertent and intermittent intrusion by exploratory drilling for resources (other than any resources provided by the disposal system itself).

PC1.016(B) PART CRITERION:

Each intrusion is assumed to be an isolated occurrence, such that a particular intruder intrudes only once.

PC1.016(C) PART CRITERION:

The assessments assumed that systematic or persistent exploitation within the controlled area do not occur.

PC1.016(D) PART CRITERION:

The consequences of human intrusion events are evaluated and included in the record.

RC1.017 RCD CRITERION:

Human intrusion events shall not be included in the quantitative modeling of total system performance of the repository.

PC1.017 PART CRITERION:

Human intrusion events are not included in the quantitative modeling of total system performance of the repository.

RC1.018 RCD CRITERION:

The compliance models for 191 and 268 shall simulate the expected behavior (processes and events) of the repository, including the potential for migration of radionuclides and hazardous constituents from the time of emplacement to 10,000 years after closure.

PC1.018 PART CRITERION:

The compliance models for 191 and 268 simulate the expected behavior (processes and events) of the repository, including the potential for migration of radionuclides and hazardous constituents from the time of emplacement to 10,000 years after closure.

RC1.019 RCD CRITERION:

The physical descriptions of the system for all models shall be identical.

PC1.019 PART CRITERION:

The physical descriptions of the system for all models for both 40 CFR 191 and RCRA are identical.

RC1.020 RCD CRITERION:

The conceptual models for the repository system, on which the mathematical and computational models are based, shall be comparable for all compliance analyses.

PC1.020 PART CRITERION:

The conceptual models for the repository system, on which the mathematical and computational models are based, are comparable for all compliance analyses.

RC1.021 RCD CRITERION:

The quantitative compliance models shall predict expected releases from a repository and shall demonstrate that the expected cumulative releases of radionuclides or concentrations of hazardous constituents will not exceed applicable standards.

PC1.021(A) PART CRITERION:

The quantitative compliance models predict expected releases from the repository

PC1.021(B) PART CRITERION:

The quantitative compliance models demonstrate that the expected cumulative releases of radionuclides does not exceed applicable standards.

PC1.021(C) PART CRITERION:

The quantitative compliance models demonstrate that the expected concentrations of hazardous constituents do not exceed applicable standards.

RC1.022 RCD CRITERION:

To demonstrate compliance with 191, the results of performance assessments shall be presented in a single CCDF that indicates the probability of exceeding various levels of cumulative release.

PC1.022(A) PART CRITERION:

For 40 CFR 191 compliance, the results of performance assessments are presented in a single CCDF.

PC1.022(B) PART CRITERION:

The CCDF in PC1.022(a) indicates the probability of exceeding various levels of cumulative release.

RC1.023 RCD CRITERION:

The justification for the selection or generation of the single CCDF shall be documented.

PC1.023 PART CRITERION:

Justification for the selection or generation of the single CCDF are documented.

RC1.024 RCD CRITERION:

The performance assessment model(s) for 191.15 shall be used to estimate the annual dose equivalent from the disposal system to any member of the public in the accessible environment for the first 1,000 years after disposal. The assessments shall consider only undisturbed performance and shall not consider water wells within the boundary of the controlled area.

PC1.024(A) PART CRITERION:

The performance assessment model(s) for 191.15 are used to estimate the annual dose equivalent from the disposal system to any member of the public in the accessible environment for the first 1,000 years after disposal.

PC1.024(B) PART CRITERION:

The assessments in PC1.024(a) consider only undisturbed performance

PC1.024(C) PART CRITERION:

The assessment in PC1.024(a) does not consider water wells within the boundary of the controlled area.

RC1.025 RCD CRITERION

Compliance models for the 191 performance assessment and the 264 and 268 environmental performance standards shall be evaluated and documented.

PC1.025 PART CRITERION

Compliance models for the 191 performance assessment and the 264 and 268 environmental performance standards are documented.

RC1.026 RCD CRITERION:

The evaluation and documentation of the model results shall include

(1) the simplifying assumptions in the conceptual, mathematical, and computational models;

(2) the rationale for the selection of the hazardous constituents and radionuclides included in the model;

(3) information demonstrating that the predictions of waste migration were calibrated for the specific site conditions, physical features, and waste emplaced at the repository;
(4) a demonstration that the modeling results are consistent with actual field measurements and that the modeling results are representative of the actual physical system; and
(5) a comparison of the model results and an explanation of any differences.

PC1.026 PART CRITERION:

The evaluation and documentation of the model results include:

(a) the simplifying assumptions in the conceptual, mathematical, and computational models;
(b) the rationale for the selection of the hazardous constituents and radionuclides included in the model;
(c) information demonstrating that the predictions of waste migration were calibrated for the specific site conditions, physical features, and waste emplaced at the repository;
(d) a demonstration that the modeling results are consistent with actual field measurements and that the modeling results are representative of the actual physical system; and
(e) a comparison of the model results and an explanation of any differences.

RC1.027 RCD CRITERION:

Sensitivity and uncertainty analyses of the compliance modeling shall be conducted. The evaluation, shall include

(1) the uncertainty in events and processes;
(2) the likelihood and consequences of alternative conceptual models;
(3) the representation of model parameters;
(4) sensitivity studies of the models; and
(5) an assessment of the accuracy of the model, including model verification results.

PC1.027 PART CRITERION:

Sensitivity and uncertainty analyses of the compliance modeling are being conducted. The evaluation include

(a) the uncertainty in events and processes;
(b) the likelihood and consequences of alternative conceptual models;
(c) the representation of model parameters;
(d) sensitivity studies of the models; and
(e) an assessment of the accuracy of the model, including model verification results.

2.0 REPOSITORY SITE CRITERIA

RC2.001 RCD CRITERION:

For geologic repositories, the boundaries of the controlled area, defined for 191, and the unit boundary, defined for 264, Subpart X, shall be coincident and shall be described in the documentation accompanying the compliance analyses.

PC2.001(A) PART CRITERION:

The boundaries of the controlled area, defined for 191, and the unit boundary, defined for 264, Subpart X, are coincident.

PC2.001(B) PART CRITERION:

The boundaries are described in the documentation accompanying the compliance analyses.

RC2.002 RCD CRITERION:

The controlled area and unit boundary shall not extend more than 5 kilometers from the outermost extent of emplaced waste and shall not exceed a total surface area of 100 square kilometers. The controlled area and unit boundary shall extend downward from the surface to a depth and configuration that is appropriate to the repository site.

PC2.002(A) PART CRITERION:

The controlled area and the unit boundary are defined.

PC2.002(B) PART CRITERION:

The controlled area and unit boundary are utilized as the point of compliance for 40 CFR 191 and RCRA.

PC2.002(C) PART CRITERION:

The controlled area and unit boundary do not extend more than 5 kilometers from the outermost extent of the emplaced waste.

PC2.002(D) PART CRITERION:

The controlled area and the unit boundary do not exceed a total area on the surface of 100 square kilometers.

PC2.002(E) PART CRITERION:

The controlled area and unit boundary extend downward from the surface to a depth and configuration that is appropriate at the repository site.

3.0 REPOSITORY OPERATIONS CRITERIA

Since the scope of the review was limited to performance assessment activities for post-closure RCRA and 40 CFR 191 Subpart B (disposal), the Repository Operation criteria were not reviewed.

4.0 NATURAL SYSTEM CRITERIA

RC4.001 RCD CRITERION:

A comprehensive, detailed description of the geology and surface and groundwater hydrology of the repository site and setting shall be provided. The description shall include an analysis of the geochemistry of the system relevant to radionuclide or contaminant migration, including a characterization of rock, soil, air and water chemistry.

PC4.001(A) PART CRITERION:

An analysis of the geochemistry of the system relevant to radionuclide or contaminant migration, including a characterization of rock, soil, air and water chemistry are being conducted.

PC4.001(B) PART CRITERION:

A comprehensive, detailed description of the geology and surface and groundwater hydrology of the repository site and setting is provided.

SPECIAL SOURCES OF GROUNDWATER

RC4.002 RCD CRITERION:

An evaluation to determine whether special sources of groundwater exist within the controlled area or less than five kilometers beyond the controlled area shall be conducted.

PC4.002(A) PART CRITERION:

An evaluation has been completed, has started, or is being planned to determine whether special sources of groundwater exist within the controlled area or less than five kilometers beyond the controlled area.

PC4.002(B) PART CRITERION:

If the evaluation has been completed, special sources of groundwater have not been found to exist within the controlled area or less than five kilometers beyond the controlled area.

5.0 WASTE CHARACTERIZATION CRITERIA

Since the scope of the review was limited to performance assessment activities for post-closure RCRA and 40 CFR 191 Subpart B (disposal), the Waste Characterization criteria were not reviewed.

6.0 ENGINEERED BARRIER SYSTEM CRITERIA

RC6.001 RCD CRITERION

The engineered barrier system shall be designed to be physically and geochemically compatible with the natural barrier system so that interactions with the natural system do not compromise the ability of the repository to meet applicable release limits.

PC6.001(A) PART CRITERION:

Proposed engineered barrier systems are designed to be physically compatible with the natural barrier system.

PC6.001(B) PART CRITERION:

Proposed engineered barrier systems are designed to be geochemically compatible with the natural barrier system.

RC6.002 RCD CRITERION:

The analyses of engineered barriers shall be supported by analytical data developed to assess their adequacy.

PC6.002(A) PART CRITERION:

Analytical data are being collected to evaluate the engineered barriers.

PC6.002(B) PART CRITERION:

Criteria are established to determine the requirements of the barrier system.

PC6.002(C) PART CRITERION:

Requirements are established to assure that the engineered system will be adequate to allow the repository to meet the release limits.

7.0 INSTITUTIONAL BARRIERS

Since the scope of the review was limited to performance assessment activities for post-closure RCRA and 40 CFR 191 Subpart B (disposal), the Institutional Barrier criteria were not reviewed.

8.0 ADMINISTRATIVE OPERATIONS

Since the scope of the review was limited to performance assessment activities for post-closure RCRA and 40 CFR 191 Subpart B (disposal), the Administrative Operations criteria were not reviewed. Although 40 CFR Part 191 does not require quality control of the computer codes, it appears necessary for a certification of compliance.

Table A-1

1.0 GENERAL COMPLIANCE CRITERIA

Criterion Number	PART Criterion	Comment
PC1.001	The PART reviewed the following criteria to establish if WIPP will comply with the applicable portions of 40 CFR 191, 264, and 268 with regard to performance assessment.	Since the performance assessment activities for compliance with 40 CFR 268.6 have not been developed as completely as those for 40 CFR 191 compliance, comments in this section are not appropriate for 40 CFR 268.6 activities unless specifically stated.
PC1.002(a)	The PA modeling activities utilize the quantitative radionuclide release limits of 40 CFR 191.13(a), 191.15, and 191.16 for the determination of compliance to 40 CFR 191.	The current PA modeling does use the quantitative release limits in §191.13(a). However, §191.15 and §191.16 require predictions based on undisturbed performance of the repository. For the undisturbed repository, SNL predicts no releases.
PC1.002(b)	The PA activities utilize the health-based limits, established pursuant to 264.601 and 268.6(a) for the determination of compliance with RCRA.	The information provided to the PART was not sufficient for the PART to draw a conclusion.
PC1.003(a)	The PA modeling addresses releases from all pathways, including groundwater, surface water, soil, and air, at the boundary of the control area of the repository.	Within the scope of the PART review, documented evidence was not found as to why some scenarios were not considered and why others were not further investigated. If some scenarios were reviewed and later dismissed, these activities were not substantiated in the documentation reviewed by the PART.
PC1.003(b)	The boundary of the control area of the repository is equivalent to the lateral extent of the unit boundary established for RCRA.	Currently, the Unit Boundary defined in the WIPP No-Migration Determination for the Test Phase is defined differently than the controlled area. DOE and the Environmental Protection Agency are discussing the possibility of re-defining the unit boundary for the disposal, closure and post-closure phases.
PC1.004	The quantitative computational model and the qualitative analysis for disposal system performance are supported by laboratory and field studies, as well as expert judgements.	Yes, conceptual models and qualitative analysis are supported by some amount of laboratory and field studies and expert judgement, but in many cases the studies are still incomplete.
PC1.005	The SNL PA and the WID compliance staffs are documenting the basis for demonstrating that the geologic disposal system complies with 191.13, 264.601, and 268.6.	Yes, but the documentation needs to be improved, especially the history of scenario development.
PC1.006	The records include the quantitative and qualitative evidence that was used to develop the performance assessment models as well as supplementary information (e.g., natural analogues, evidence that supports the process models, parameter ranges, geometric conceptual model(s), hypotheses, and simplifying assumptions used).	Yes, but this documentation needs to be improved.
PC1.007	The SNL PA and WID compliance staffs are incorporating new information relevant to the performance of the disposal system in the compliance analysis.	Yes.

Table A-1

1.0 GENERAL COMPLIANCE CRITERIA

Criterion Number	PART Criterion	Comment
PC1.008(a)	Performance of the disposal system is being evaluated based on the projected contributions of both natural and engineered barriers.	None of the conceptual models describing shaft and drift seal behavior have been incorporated into the performance assessment analyses for preliminary comparison with 40 CFR 191 or 40 CFR 268.6. The existing models used for performance assessment analyses do not include a representation of the shaft, borehole or drift seals. The importance of engineered barriers is recognized by the scientific and management staff supporting WIPP and these features will reportedly be incorporated in subsequent (FY 94) performance assessment analyses.
PC1.008(b)	It is being demonstrated that the barrier system controls, minimizes, or eliminates releases.	Similar to the response for criterion PC1.008(a), it is not possible to demonstrate the contribution of the barrier system at this time because the system model does not include all of the engineered barrier and natural system components.
PC1.009(a)	All components of the geologic disposal system, including the characteristics and radionuclide content of the emplaced waste, are considered when predicting the system performance.	No. Some components of the repository system have not been included in PA analysis to date.
PC1.009(b)	Components which make a negligible contribution to the overall system performance are not considered.	Not enough information was available to the PART to draw a conclusion.
PC1.011	The pathways evaluated by SNL for the analysis to the containment requirements of 191.13 and the individual protection requirements of 191.15 are consistent with the pathways evaluated by WID for demonstrating compliance with the environmental performance standard of 264.601 and the no-migration standard of 268.6.	Not enough information was available from WID to draw a conclusion.
PC1.012	The compliance analyses consider the likelihood and consequences of events and processes that may disturb the disposal system, including earthquakes, floods, severe storm events, droughts, and other natural phenomena.	The analysis may have considered these events, but they were not substantiated in the documentation reviewed by the PART.
PC1.013(a)	The PA staff developed a process to consider many potential processes and events.	Yes.
PC1.013(b)	A process assigns a probability to each process or event.	Yes, but the scenarios used for construction of the CCDFs are defined differently than the scenarios in the scenario selection process. SNL uses a mathematical construction through sampling to define scenarios, which, in some scenarios, leads to a probability equal to the reciprocal of the number of cases.
PC1.013(c)	Processes or events with likelihood of less than 1 chance in 10,000 over 10,000 years are removed from further consideration.	Documentation was not adequate to draw a conclusion.

Table A-1

1.0 GENERAL COMPLIANCE CRITERIA

Criterion Number	PART Criterion	Comment
PC1.013(d)	For remaining processes or events, an evaluation of the ability of the disposal system to isolated wastes if the event or process occurs is being conducted.	Documentation was not adequate to draw a conclusion.
PC1.013(e)	The consequences of the occurrence of the process or event are evaluated.	Yes.
PC1.014(a)	Natural processes and events are being analyzed as part of the performance assessment.	Yes.
PC1.014(b)	It is being demonstrated with reasonable expectation that natural processes and events do not result in a release of radionuclides or hazardous constituents in excess of applicable standards.	This determination of "reasonable expectation" of compliance is outside the scope of the PART.
PC1.015(a)	Consideration is given to controls that will be imposed to make human intrusion unlikely.	Yes.
PC1.015(b)	An evaluation of the effectiveness of permanent markers is being conducted.	Yes.
PC1.015(c)	The judgement of the likelihood of human intrusion is based primarily on the evaluation stated in PC1-015(b).	Yes.
PC1.015(d)	The likelihood of human intrusion is being evaluated.	Yes.
PC1.016(a)	Human intrusion events are considered to be no more severe than inadvertent and intermittent intrusion by exploratory drilling for resources (other than any resources provided by the disposal system itself).	Yes.
PC1.016(b)	Each intrusion is assumed to be an isolated occurrence, such that a particular intruder intrudes only once.	Yes.
PC1.017(c)	The assessments assumed that systematic or persistent exploitation within the controlled area do not occur.	Yes.
PC1.016(d)	The consequences of human intrusion events are evaluated and included in the record.	Yes.
PC1.017	Human intrusion events are not included in the quantitative modeling of total system performance of the repository.	This criterion has been eliminated from the RCD.

Table A-1

1.0 GENERAL COMPLIANCE CRITERIA

Criterion Number	PART Criterion	Comment
PC1.018	The compliance models for 191 and 268 simulate the expected behavior (processes and events) of the repository, including the potential for migration of radionuclides and hazardous constituents from the time of emplacement to 10,000 years after closure.	No. The expected behavior of the repository was not simulated due to inadequate information on shaft and panel seals, unknown gas generation potential and rate, incomplete retardation experiments, lack of verification of Culebra modeling, incomplete information on coupled response and on time dependent behavior of the DRZ and engineered barriers. No information was available on compliance models for 40 CFR 268.
PC1.019	The physical descriptions of the system for all models for both 40 CFR 191 and RCRA are identical.	Insufficient information on 40 CFR 268 activities to draw a conclusion.
PC1.020	The conceptual models for the repository system, on which the mathematical and computational models are based, are comparable for all compliance analyses.	Insufficient information on 40 CFR 268 activities to draw a conclusion.
PC1.021(a)	The quantitative compliance models predict expected releases from the repository.	See PC1.008
PC1.021(b)	The quantitative compliance models demonstrate that the expected cumulative releases of radionuclides does not exceed applicable standards.	The intent of the PA effort is to lead to this conclusion. Insufficient evidence is available at this time to make this determination.
PC1.021(c)	The quantitative compliance models demonstrate that the expected concentrations of hazardous constituents do not exceed applicable standards.	The intent of the PA effort is to lead to this conclusion. Insufficient evidence is available at this time to make this determination.
PC1.022(a)	For 40 CFR 191 compliance, the results of performance assessments are presented in a single CCDF.	Yes.
PC1.022(b)	The CCDF in PC1.022(a) indicates the probability of exceeding various levels of cumulative release.	Yes.
PC1.023	Justification for the selection or generation of the single CCDF are documented.	Yes.
PC1.024(a)	The performance assessment model(s) for 191.15 are used to estimate the annual dose equivalent from the disposal system to any member of the public in the accessible environment for the first 1,000 years after disposal.	Current SNL analysis predicted no releases from the undisturbed repository. However, no documentation was provided to the PART.
PC1.024(b)	The assessments in PC1.024(a) consider only undisturbed performance.	Insufficient information was available to draw a conclusion.

Table A-1

1.0 GENERAL COMPLIANCE CRITERIA

Criterion Number	PART Criterion	Comment
PC1.024(c)	The assessment in PC1.024(a) does not consider water wells within the boundary of the controlled area.	Insufficient information was available to draw a conclusion.
PC1.025	Compliance models for the 191 performance assessment and the 264 and 268 environmental performance standards are documented.	No. Few if any of the compliance models have been documented at the "Class A" level. Since most, if not all, of the SNL models have been developed in-house, these models must be subjected to a rigorous review process to be classified as "Class A".
PC1.026	The evaluation and documentation of the model results include: (a) the simplifying assumptions in the conceptual, mathematical, and computational models; (b) the rationale for the selection of the hazardous constituents and radionuclides included in the model; (c) information demonstrating that the predictions of waste migration were calibrated for the specific site conditions, physical features, and waste emplaced at the repository; (d) a demonstration that the modeling results are consistent with actual field measurements and that the modeling results are representative of the actual physical system; and (e) a comparison of the model results and an explanation of any differences.	This aspect of the program is still being developed. Although there is evidence that this criterion will eventually be satisfied, these activities currently are not well documented.
PC1.027	Sensitivity and uncertainty analyses of the compliance modeling are being conducted. The evaluation include (a) the uncertainty in events and processes; (b) the likelihood and consequences of alternative conceptual models; (c) the representation of model parameters; (d) sensitivity studies of the models; and (e) an assessment of the accuracy of the model, including model verification results.	The sensitivity analysis conducted to date have been utilized to investigate parameter uncertainties, not conceptual model uncertainties. The use of sensitivity studies for the conceptual models would lead to increased confidence in the models. One area in particular where additional sensitivity analyses would be useful is in connecting the detailed deterministic models developed by the principal investigators to the simplified probabilistic models used by performance assessment. The sensitivity and uncertainty analysis would be very useful is specify the limited range in which the simplified models are valid.

Table A-2

2.0 REPOSITORY SITE CRITERIA

Criterion Number	PART Criterion	Comment
PC2.001(a)	The boundaries of the controlled area, defined for 191, and the unit boundary, defined for 264, Subpart X, are coincident.	See comments on PC1.003(b)
PC2.001(b)	The boundaries are described in the documentation accompanying the compliance analyses.	Yes
PC2.002(a)	The controlled area and the unit boundary are defined.	The controlled area for 40 CFR 191 is defined by the WIPP boundary in the WIPP Land Withdrawal Act (P.L. 102-579). The RCRA unit boundary has been defined for the WIPP Test Phase in the No-Migration Determination.
PC2.002(b)	The controlled area and unit boundary are utilized as the point of compliance for 40 CFR 191 and RCRA.	Yes
PC2.002(c)	The controlled area and unit boundary do not extend more than 5 kilometers from the outermost extent of the emplaced waste.	Yes
PC2.002(d)	The controlled area and the unit boundary do not exceed a total area on the surface of 100 square kilometers.	Yes
PC2.002(e)	The controlled area and unit boundary extend downward from the surface to a depth and configuration that is appropriate at the repository site.	No, currently the unit boundary defined by the WIPP No-Migration Determination

Table A-3

NATURAL SYSTEM CRITERIA

Criterion Number	PART Criterion	Comment
PC4.001(a)	An analysis of the geochemistry of the system relevant to radionuclide or contaminant migration, including a characterization of rock, soil, air and water chemistry are being conducted.	An analysis is being done, but the current modeling does not permit SNL to address chemistry. This aspect of the analysis is just commencing.
PC4.001(b)	A comprehensive, detailed description of the geology and surface and groundwater hydrology of the repository site and setting is provided.	SNL has developed a detailed description of the local geology and hydrology for the large scale. On a small scale, this work is very difficult. The groundwater hydrology has the least detailed description.
PC4.002(a)	An evaluation has been completed, has started, or is being planned to determine whether special sources of groundwater exist within the controlled area or less than five kilometers beyond the controlled area.	[THIS CRITERION WAS NOT EVALUATED]
PC4.002(b)	If the evaluation has been completed, special sources of groundwater have not been found to exist within the controlled area or less than five kilometers beyond the controlled area.	This evaluation has not been completed.

Table A-4

ENGINEERED BARRIER SYSTEM CRITERIA

Criterion Number	PART Criterion	Comment
PC6.001(a)	Proposed engineered barrier systems are designed to be physically compatible with the natural barrier system.	An analysis by Arguello indicates that the stresses in the unreinforced concrete bulkheads in the panel and lower shaft seals may exceed the strength of the concrete. The maximum stresses occur within the first 5 years after installation of the seal. Based on these results, it appears the bulkheads will require some type of reinforcement to accommodate the tensile and compressive stresses generated during the compaction period.
PC6.001(b)	Proposed engineered barrier systems are designed to be geochemically compatible with the natural barrier system.	The only long-term component in the panel and shaft seals is crushed salt which is chemically compatible (stable) in the Salado Formation. The other components of the seals (bentonite and concrete) are unlikely to be significantly affected by the chemical conditions present over the time period they must function (hundreds of years). A salt water based concrete has been developed by SNL to minimize the chemical disequilibrium present. Cementitious grout is being considered as a sealant for MB 139 below the panel seal areas to reduce the likelihood that the interbed will serve as a bypass around the seals. The performance requirements associated with the material would presumably be relevant for long time periods and the issue of longevity and chemical compatibility becomes important. This issue has not been resolved.
PC6.002(a)	Analytical data are being collected to evaluated the engineered barriers.	SNL has performed a series of analyses to investigate the significance and relationship between the processes and events that are likely to be present in the WIPP repository system and the engineered barrier system. The analyses have focused on the expected creep closure of the underground openings, consolidation of the crushed salt seal components, stresses in the concrete bulkheads, the influence brine inflow may have on consolidation, and the potential for gas and brine migration through the DRZ and anhydrite interbeds. Additional analyses are underway to address some of these issues in greater detail and incorporate the most important ones in the performance assessment models.
PC6.002(b)	Criteria are established to determine the requirements of the barrier system.	The required performance of the engineered barrier system and its components can only be developed after they have been incorporated in the performance assessment system model. Because the seals have not been incorporated in existing performance assessment analyses, quantitative performance criteria cannot be assigned.
PC6.002(c)	Requirements are established to assure that the engineered system will be adequate to allow the repository to meet the release limits.	See PC1.008(a) and (b)

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

BSEP	Brine Sampling and Evaluation Program
CCDF	Complementary cumulative distribution function
CDF	Cumulative distribution function
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
CH	Contact-handled
DAM	Design Analysis Model
DNFSB	Defense Nuclear Facility Safety Board
DOE	Department of Energy
DRZ	Disturbed rock zone
EEG	New Mexico's Environmental Evaluation Group
EM-342	The Environmental Restoration and Waste Management WIPP Project Management Division (of DOE)
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEIS	Final Environmental Impact Statement
FSAR	Final Safety Analysis Report
FSEIS	Final Supplemental Environmental Impact Statement
HSWA	Hazardous and Solid Waste Amendments
LWA	Land Withdrawal Act
MB	Marker Bed
NAS	National Academy of Science
NEPA	National Environmental Policy Act
NIOSH	National Institute of Occupational Safety and Health
NMD	No-migration determination
NMED	New Mexico Environmental Department
NMVP	No-migration variance petition
NRC	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
PA	Performance Assessment
PANRG	Performance Assessment National Review Group
PART	Performance Assessment Review Team
PDF	Probability density function
PI	Principal Investigator
POR	Probability of Release
QA	Quality Assurance
RCD	Regulatory Criteria Document
RCRA	Resource Conservation and Recovery Act
RH	Remote-handled
RIP	Repository Integration Program
SAR	Safety Analysis Report
SNL	Sandia National Laboratories
SNR	Summed Normalized Releases
SPDV	Site and Preliminary Design Validation
SWB	Standard waste box
SWDA	Solid Waste Disposal Act
TDEM	Time domain electromagnetic methods
TDS	Total dissolved solid
TPPW	Test Phase Plan for WIPP
TRU	Transuranic
TSG	Technical Support Group
TSI	Thermal/structural interactions
USGS	United States Geological Survey
VOC	Volatile organic carbons
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WPIO	WIPP Project Integration Office
WPSO	WIPP Project Site Office

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