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Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP)

John C. Stormont

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Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP)

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Abstract

This report presents the current intentions and directions of the WIPP Plugging and Sealing Program. The Plugging and Sealing Program is responsible for developing the design basis and criteria for sealing the penetrations (boreholes, shafts, and drifts) associated with the WIPP. Estimates of sealing requirements indicate that the technical requirements for sealing will not be great. Conceptual designs presented in this report call for the use of salt, cementitious materials, and clay in the form of seals (or bulkheads) and backfills. The state of knowledge and remaining technical concerns for sealing the WIPP facility are reviewed; and a program of laboratory, field, and modeling efforts to resolve these issues is described.

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Acronyms

BCT	Bell Canyon Test
BCF	Bell Canyon Formation
DHLW	Defense high-level waste
DMG	Delaware Mountain Group
DOE	US Department of Energy
EPA	Environmental Protection Agency
FEIS	Final Environmental Impact Statement
ISBT	In Situ Bulkhead Test
NWTS	National Waste Terminal Storage
QA	Quality Assurance
R&D	Research and development
SAR	Safety Analysis Report
SNL	Sandia National Laboratories
SNM	State of New Mexico
TRU	Transuranic
TSI	Thermal/Structural Interaction
WES	Waterways Experiment Station
WIPP	Waste Isolation Pilot Plant
WPC	WIPP Plugging Criteria
WPP	Waste Package Performance

Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP)

1. Introduction

The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) facility in southeast New Mexico. The mission of the WIPP facility is

“... for the express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive waste resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission.” (Public Law 96-164).

Thus the WIPP facility will demonstrate transuranic (TRU) waste disposal and in situ emplacement, testing, and retrieval of defense high-level waste (DHLW) in bedded salt.

A part of the WIPP Research and Development (R&D) Program conducted by Sandia National Laboratories (SNL) is the Plugging and Sealing Program.* The activities of the Plugging and Sealing Program will result in acceptable sealing technology for the WIPP based on a technical program of modeling, laboratory materials testing, and field testing. The objectives of the Plugging and Sealing Program are

- To develop candidate materials for sealing that are compatible with the WIPP stratigraphy
- To evaluate host-rock properties that will influence seal design and performance
- To assess long-term geochemical and mechanical stability of candidate materials
- To evaluate emplacement techniques and the performance of various types of seals
- To provide design information for seals and for emplacement techniques
- To assess the impact of leakage resulting from man-made penetrations on the performance of the repository system.

*A “seal” is considered to be a more flow-restrictive barrier than is a “plug.” A distinction between the two is often not possible, and in fact may change with time. In this report, the terms are treated as synonymous.

The Plugging and Sealing Program will provide the technical basis and criteria for sealing the penetrations associated with the WIPP: *vertical penetrations* (boreholes and shafts) and *horizontal penetrations* (access drifts and storage rooms). This sealing may be in the form of bulkheads, backfills, borehole and shaft seals, and other appropriate barriers. The Plugging and Sealing Program does not specifically consider backfill surrounding the waste canister in emplacement holes, although some of the investigations in this area being conducted by the Waste Package Program may provide information for the WIPP Plugging and Sealing Program.

The basic goal of the sealing system is to minimize the release of radionuclides resulting from man-made penetrations into the WIPP. Evaluating potential scenarios (Bingham and Barr, 1978) revealed that groundwater is the most credible mechanism for the waste to migrate between the disposal horizon and the biosphere. Thus, the primary function of the barriers is to limit fluid migration in, through, and out of the repository. The objective of these barriers is to ensure minimizing the amount of radioactivity reaching the biosphere to acceptable safe levels. Total exclusion of radioactivity reaching the biosphere is not required since “perfect” seals may not be possible or practical; they are certainly not verifiable; and, most important, they are not necessary, as indicated by previous consequence assessments. (US DOE, 1980; Intera Environmental Consultants, Inc., 1981; US DOE, WIPP, 1980).

Developing technologies for barrier emplacement requires understanding that the actual sealing activity is meant to be accomplished by DOE contracts to commercial industries. Therefore, emphasis will be given to potential modifications and extrapolations of current industrial capabilities. This approach should help to minimize unnecessary costs and to assist in transferring technologies. Consideration will be given to the engineering economics of various designs as part of the Plugging and Sealing Program.

The Plugging and Sealing Program focuses on the site-specific stratigraphy, hydrologic characteristics,

and facility design of the WIPP. However, information on materials development, test techniques, and field data will undoubtedly be useful to and supportive of the National Waste Terminal Storage (NWTS) program (Hunter, 1982).

This report briefly describes the stratigraphy and the WIPP facility, presents estimates of sealing requirements, discusses sealing design concepts, and updates pertinent issues and the technical direction of the Plugging and Sealing Program as described in previous reports (Christensen and Hunter, 1979; Hunter, 1980; Hunter, 1982; Christensen, Lambert, and Gulick, 1982). In the context of this report, issues are information needs and technical concerns whose resolution will contribute toward developing adequate sealing technology for the WIPP. This report reflects the work Sandia has determined is necessary to accomplish the WIPP objectives, but does not necessarily imply DOE programmatic approval.

2. Stratigraphy and Facility Design

2.1. Site Stratigraphy

Figure 1 shows the generalized WIPP site stratigraphy. The lithology from the surface to ~550 ft (168 m) is referred to as the Dewey Lake Red Beds, consisting of alluvia, sandstones, siltstones, and mudstones. The Rustler Formation, from 550 ft (168 m) to 850 ft (257 m) below the surface, consists of anhydrite, halite, siltstone, and dolomite. The Rustler contains the ~25-ft(8-m)-thick, water-bearing Magenta and Culebra dolomite beds at ~ 610 ft (186 m) and 720 ft (220 m), respectively. These aquifers have produced up to 1 gal/min (3.8 L/min) into an unlined 6-ft(2-m)-dia shaft (Black, Newton, and Shukla, 1983). The Salado Formation, from the base of the Rustler to 2800 ft (850 m) below the surface, is primarily halite but also includes thin beds of anhydrite, polyhalite, clay zones, and, in some areas, potash minerals. The Castile extends from the Salado to 4000 ft (1220 m). It consists of thick anhydrite and halite beds. Below the Castile is the 4000-ft(1220-m)-thick Delaware Mountain Group (DMG), which consists of sandstones, limestones, and shales. The Bell Canyon Formation (BCF) is located within the DMG ~100 ft (30 m) below the Castile-DMG interface, with an average conductivity of 0.016 ft/day (0.005 m/day) (Powers et al, 1978) in the isolated beds of sandstones ~20 ft (6 m) thick. A complete geologic and hydrologic characterization of the WIPP site is contained in Powers et al (1978).

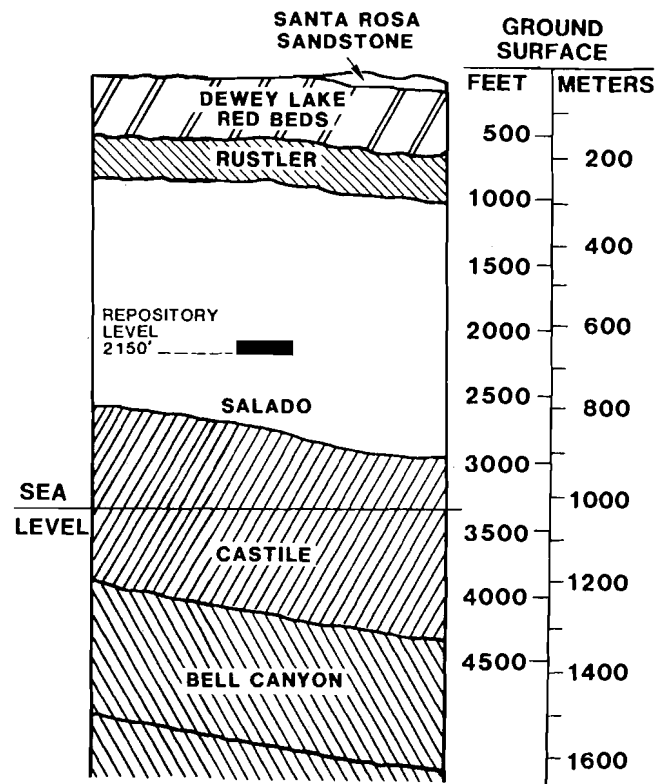


Figure 1. Generalized WIPP Site Stratigraphy

Sealing activities for the WIPP will address only the Rustler, Salado, and Castile Formations. The Dewey Lake Red Beds and sandstone formations below the Castile will not require special plugging for waste isolation, but must conform with existing statutes of the State of New Mexico. These formations are the more permeable, less competent zones in which a plug adds little to restricting fluids because the zones themselves are relatively permeable (Christensen, Lambert, and Gulick, 1982).

2.2. Facility Design

The proposed WIPP facility (Figure 2) is to be located at 2150 ft (660 m) below the surface in the Salado Formation. These three shafts will provide access from the surface to the WIPP:

- Construction and salt-handling shaft (12 ft (3.7 m) drilled diameter), for ventilation intake (downcast) and removing salt
- Waste shaft (20 ft (6.1 m) slashed diameter), for transporting waste in and out of the repository
- Exhaust shaft (15 ft (4.6 m) slashed diameter), for ventilation exhaust.

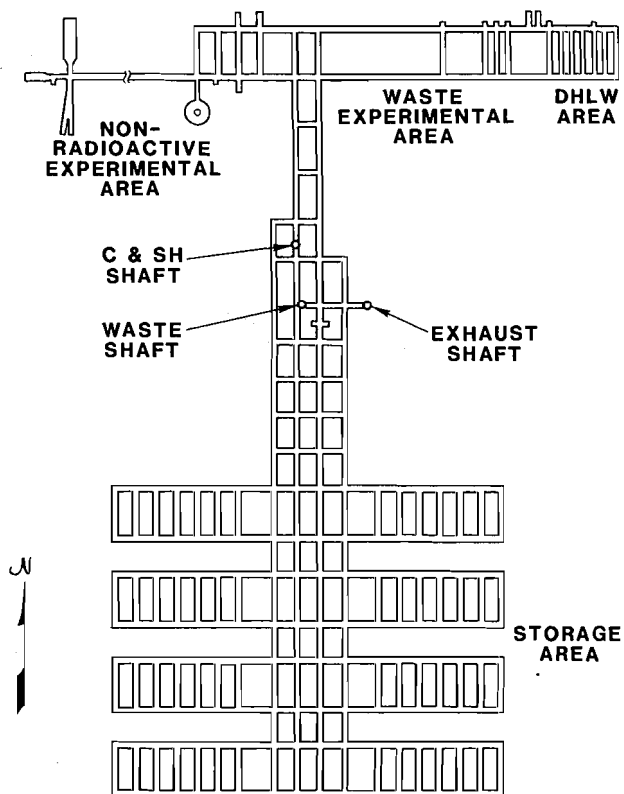


Figure 2. Plan View of Proposed WIPP Facility

The underground development (Figure 2) can be separated into areas north and south of the shafts. To the north of the shaft stations are the experimental areas. Experiments will be conducted under ambient and simulated waste (heated) conditions, as well as with actual DHLW. These experiments, indicated by prior model development, laboratory testing, and field testing, seek to establish confidence in waste isolation by providing adequate understanding of various phenomena and by validating analytical procedures and systems designs (Matalucci et al, 1982). It is planned to remove all DHLW canisters containing radioactivity for demonstrations and experimentation and to decontaminate the area to specified levels (US DOE, 1980).

To the south of the shaft, stations will be the TRU disposal rooms. Four main north-south drifts will provide access to the eight disposal panels. Each panel will consist of seven parallel rooms 13 ft (4 m) high by 33 ft (10 m) wide accessed by submain drifts to the north and south of the disposal rooms.

3. Sealing Requirements

3.1. Perspective

A necessary step in determining seal design specifications (parameters to ensure a specified performance) is to determine the seal performance required for limiting the release of radionuclides to an acceptable level. Specific performance requirements for the sealing system at the WIPP have not yet been established. However, we anticipate that the draft standards of the Environmental Protection Agency (EPA) for disposal of TRU waste (US EPA, 1982) will require engineered barriers as part of the defense-in-depth philosophy. Planned shaft seals, panels seals, and tailored fills should satisfy the requirement for engineered barriers. Allowable radioactive releases will also be dictated by these EPA regulations. Thus, the performance of the seal system must ensure that allowable releases are not exceeded. Performance requirements will be derived after (1) finalizing regulations pertaining to isolation and allowable releases, and (2) completing the updated assessments of open and sealed penetrations that incorporate the best information available on site characteristics.

Pending specific performance requirements, the Plugging and Sealing Program will seek to develop and evaluate technology and designs for limiting release of radioactivity to as low a level as practicable and as reasonably achievable. This approach represents a best effort to ensure that, once performance requirements are stipulated, appropriate technology will be available. There is a high level of confidence that existing and developing technology can meet the performance requirements of the seal design for the WIPP.

As will be shown, previous consequence assessments (US DOE, 1980; US DOE, WIPP, 1980; Woolfolk, 1982) indicate that the existing favorable hydrologic conditions at the WIPP result in negligible radiologic consequences for open or minimally sealed penetrations. These assessments infer possibly minimal performance requirements for the seals. Regardless of these conclusions, the WIPP will be sealed to the extent deemed practical at the time of sealing and consistent with limiting release of radioactivity to as low a level as practicable and as reasonably achievable because

- A cautious and conservative approach is appropriate when public health and safety are involved
- Sealing will add to confidence in the long-term isolation of waste, particularly if it is conducive to reconstituting or reconstructing the penetration
- Sealing the penetrations is consistent with the multiple-barrier concept mandated by draft EPA standards
- Sealing will reduce public concern regarding long-term hazards.

3.2. Estimating Sealing Requirements

Results from previous consequence assessments (US DOE, 1980; US DOE, WIPP, 1980; Woolfolk, 1982) can be used to obtain an idea of the sealing that may be required at the WIPP to ensure public health and safety. This approach will indicate the magnitude of the sealing and will also aid in estimating the influence of sealing performance on radiologic doses received by exposed individuals. Appendix A contains the calculations; they are summarized below.

As will be shown, the radiologic doses from the examined scenarios are small. It is recognized that these doses, and the associated model and assumptions used to calculate them, do not establish target release levels for deriving performance requirements. Also, the calculations are quite simple although they are believed to be very conservative. The exercises are valuable, however, because they estimate radiologic consequences and the associated degree of sealing to produce those consequences.

The following sections summarize the Appendix A calculations.

3.2.1. Boreholes

The worst-case scenario in the Final Environmental Impact Statement (FEIS) (US DOE, 1980) involves an uncased, *open* borehole that penetrates the Rustler, the center of the repository, and the Bell Canyon aquifers. Dissolution of the contents of the repository from water flowing between the aquifers requires >1 my. The whole-body dose received by the maximally exposed individual is ~0.012% of the natural background radiation near the WIPP site. Subsequent hydrologic investigations and calculations indicate that the FEIS calculations are very conservative.

There are no holes within the WIPP site that pass through the upper and lower aquifers as well as the

repository. Therefore, for existing boreholes to be of consequence they must dissolve the salt separating them from the repository. In boreholes penetrating only the *upper* aquifer, the dissolution is controlled by diffusion and proceeds so slowly as to pose no threat to the WIPP even if the hole should remain open. Boreholes connecting the *upper and lower* aquifers dissolve salt faster because of the circulation established between the aquifers. Conservative calculations in Appendix A show that it would take ~4 my to enlarge the borehole radius to 1000 ft (305 m)—1000 ft horizontally from the repository boundary is the closest a borehole of this type exists at the WIPP. Subsequent dissolution and transport of the waste will necessarily result in less consequence than that of the worst-case scenario in the FEIS because the actinides will have decayed more in the time required for borehole enlargement. Plugging holes will additionally enhance confidence that the radiologic consequences have been bounded by further slowing or preventing flow in the boreholes. Appendix B contains a proposed criterion for identifying which boreholes in the vicinity of the WIPP (and that are the responsibility of the DOE) require stringent sealing in a manner exceeding existing statutory requirements.

3.2.2. Shafts

The shafts provide for direct communication between the upper aquifer and the repository. Establishing a U-tube flow down a shaft, through the repository, and up another shaft or other penetration is therefore plausible.* In the U-tube scenarios evaluated in the FEIS (US DOE, 1980) and the Safety Analysis Report (SAR) (US DOE, WIPP, 1980), resistance in the upstream and downstream wellbores and in the repository limited flow to ~2 ft³/day (0.06 m³/day). The whole-body dose received by the maximally exposed individual was calculated as <0.01% of the natural background radiation near the WIPP site.

The same flow rate as predicted in the FEIS and SAR will be achieved if the hydraulic conductance of the penetration remains constant. The hydraulic conductance, the inverse of resistance, is defined as

$$HC = \frac{KA}{L}$$

*This scenario may in fact *not* be plausible when increases in salinity (density) resulting from salt dissolution are taken into account, and when more representative hydraulic data are used.

where K is the permeability, A is the cross-sectional area, and L is the length of the seal. Thus, given the hydraulic conductance used in the FEIS and SAR and the area of the shafts, a permeability-length relationship can be defined that will result in a 2 ft³/day (0.06 m³/day) flow rate in the shafts. Figure 3 shows this relationship. Admittedly simplistic, these calculations can nevertheless account for very complicated flow by using the effective seal permeabilities. "Effective seal permeabilities" means permeability values derived by assuming that all flow occurs through the seal area. In that way, the contributions of the interface and disturbed zone are implicitly contained in any subsequent calculations. (Section 4.5 discusses the different possible flow paths.)

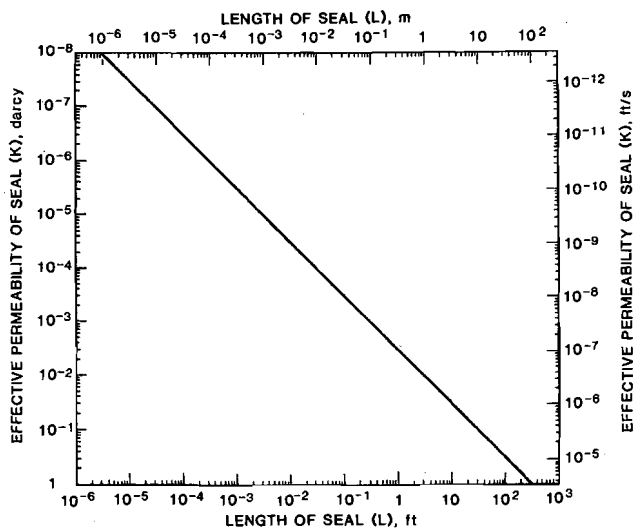


Figure 3. Length of Seal vs Permeability of Seal Required for a Flow of 2 ft³/day (0.06 m³/day) in Three 20-ft-Dia Shafts

Table 1 presents measured permeabilities of candidate sealing materials. The values given for the BCT 1-FF grout in anhydrite are effective permeabilities because the measurements encompassed the rock/seal system. These measurements suggest that the influence of the interface and disturbed zone will not result in effective permeabilities so large as to require lengthy seal sections. (Of course, testing is required to obtain effective permeabilities for other seal materials and designs.) Thus, if the performance requirement of the shaft seals was to limit flow to 2 ft³/day (0.06 m³/day), only relatively short lengths of candidate seal materials would probably be required. This implies that only short intervals may be required to be plugged in the shafts to attain the above flow rate.

3.2.3. Horizontal Penetrations (Drifts)

The same approach as with shafts can be used to calculate the lengths of various materials required to limit flow in the repository to 2 ft³/day (0.06 m³/day) in a U-tube scenario. Again, these lengths are quite short for expected effective seal permeabilities (Figure 4 and Table 1).

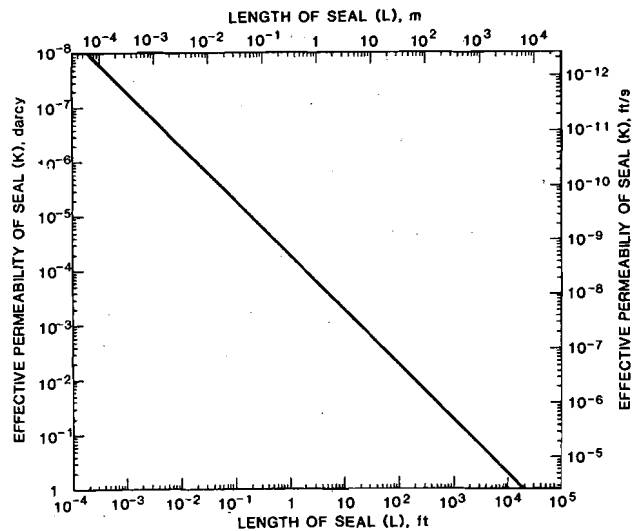


Figure 4. Length of Seal vs Permeability of Seal Required for a Flow of 2 ft³/day (0.06 m³/day) Through the Repository

Pressurized brine intrusion scenarios (Woolfolk, 1982) also imply some sealing in the drifts. The worst-case scenario assumes inundation of part of the storage area with pressurized brine, at some later date drilling a borehole to connect the repository to the surface and allowing brine to flow to the surface for 24 hr before it is stopped. This scenario assumes availability of only a limited volume of waste-contaminated brine to the release mechanism (the borehole connecting the repository and the surface). In other words, seals are required to prevent any brine outside the limited area from entering this area and reaching the surface while the borehole is open. One way to do this is to require travel times in the seals to exceed the 24-hr release period. Thus, even if the entire repository contained waste-contaminated brine, only the brine volume in the sealed area containing the borehole to the surface could be released. Figure 5 gives the relationship developed in Appendix A between effective permeability and lengths of seal needed to produce a 24-hr travel time. For candidate drift-sealing materials (Table 1) this length should be short.

Table 1. Measured Permeabilities of Candidate Sealing Materials

Material	References (see reference for test condition)	Permeability (D 10^{-6})
Rock salt (in situ)	Peterson et al, 1981	10 to 20
Rock salt (laboratory, healed)	Sutherland and Cave, 1979	0.05
Rock salt (laboratory, <i>not</i> healed*)	Cooley and Butters, 1979	1 to 100
BCT 1-FF in anhydrite	Christensen and Peterson, 1981	50
BCT 1-FF in anhydrite (laboratory)	Gulick, Boa, and Buck, 1980	0.5 to 10
BCT 1-FF (laboratory)	Gulick, Boa, and Buck, 1980	1×10^{-1}
Crushed salt** (laboratory, consolidated, healed*)	Sullivan, 1983	1×10^2 to 1×10^3
Crushed salt** (laboratory, consolidated, <i>not</i> healed)	Sullivan, 1983	1×10^3
70% crushed salt, 30% bentonite** (laboratory, consolidated)	Peterson and Kelkar, 1983	5.3×10^2
Bentonite** (laboratory, consolidated)	Peterson and Kelkar, 1983	0.34

*Healing refers to leaving the sample hydrostatically stressed for some time (typically, at least 48 hr) before making measurement.

**Backfill material permeability depends on how the material was emplaced and the time after emplacement being considered. "Consolidated" backfill may be the initial condition of a compacted backfill or a backfill that is at some stage of densification as a result of pressure from the creep closure of rock surrounding the excavation.

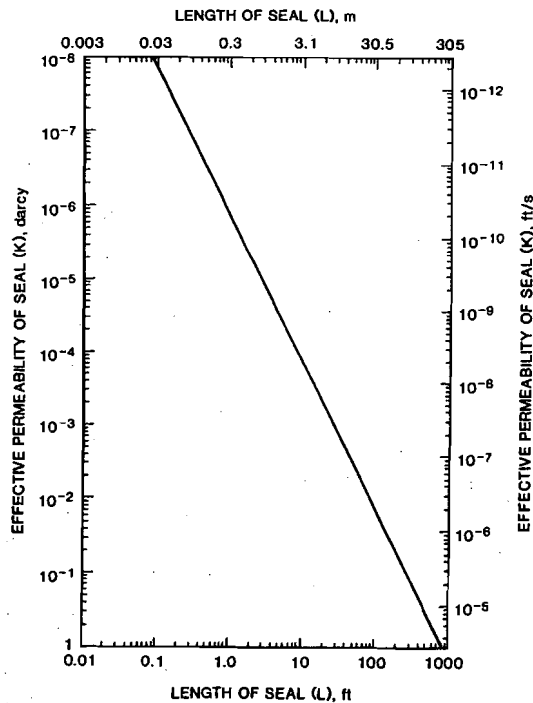


Figure 5. Length of Seal vs Permeability of Seal Required for a Travel Time >24 hr in a Seal at the WIPP Horizons

The seals must also structurally withstand the pressurized brine. Very conservative calculations indicate that a cement-based seal <15 ft long should resist the assumed maximum axial pressure of 2665 psi (18.4 MPa) by developing frictional resistance along the interface.

4. Sealing Fundamentals

Several ideas are fundamental to the plugging and sealing strategy of the WIPP. They serve as the foundation on which designs are based. These fundamentals provide for revisions and modifications resulting from future investigations.

4.1. Use of Halite

The sealing strategy for the WIPP is to use the properties of intact and fragmented salt. The following characteristics of salt are conducive to sealing:

- Openings (shafts, drifts, boreholes) in salt tend to close with time from the time-dependent deformation (creep) of the salt surrounding the excavation (Wawersik and Hannum, 1979; Li, Wu, and Antonas, 1982).
- Fractures in salt "heal" under appropriate conditions. Laboratory investigations indicate that fractures, when subjected to stresses anticipated at the WIPP for a short period, are restored to a condition approaching that of intact salt (Costin and Wawersik, 1980).
- Intact salt is almost impermeable; permeabilities are in the submicrodarcy range (Sutherland and Cave, 1979; Cooley and Butters, 1979).
- Granular salt, when subjected to sufficient pressures such as those generated by an excavation closing from creep of the surrounding salt, is expected to reconsolidate or recrystallize. This salt then potentially forms a mass whose properties may approach those of intact salt (Shor, Baes, and Canonico, 1981). The degree of final reconsolidation is presently unknown.
- Granular salt should exhibit compatibility with the host formation (Section 4.2) and should be in ample supply.

4.2. Compatibility

Real-time observance is not possible of the long-term chemical and mechanical stability of sealing materials in their host geologic environment. Models can be developed to predict long-term behavior but

become increasingly difficult to verify with increased diversity of the seal and rock material and with a lengthening time of interest. Similarity between a sealing material and its host formation enhances compatibility and long-term stability. Thus, compatibility between sealing materials and their host formations is desirable (1) to increase long-term stability of the sealing system, (2) to reduce the burden on predictive modeling, and (3) to add confidence in long-term isolation. The philosophy of compatibility, then, refers to striving toward minimizing adverse reactions between sealing materials and the host formation. Prudence dictates this even if performance requirements do not.

In its extreme, compatibility will allow restoring the formation to its preexcavated state. No preferential flow or dissolution would occur along penetrations, and the already unlikely liquid-breach scenarios (Bingham and Barr, 1978) would become even less probable. The consolidation of mined or crushed salt may offer the potential for restoring the formation to its predisturbed state. Preliminary laboratory (Holcomb and Hannum, 1982; Shor, Baes, and Canonico, 1981) and numerical (Hunter, 1982; Kelsall et al, 1982) investigations suggest an insufficient data base for confidently predicting total reconsolidation of crushed salt at the WIPP. However, even if reconstruction with crushed-salt backfill is possible, it may not apply or be appropriate in all situations because

- vertical penetrations pass through formations not containing salt,
- the time required for consolidation precludes using crushed salt as short-term barriers
- redundancy in design may dictate using other materials
- other materials may have desirable properties not possessed by crushed salt.

In the absence of perfect restoration, materials and designs should seek a large degree of compatibility between the plug and its environment. Compatibility does not dictate that a material must be completely neutral for all time. Rather, reactions that may compromise its effectiveness should be minimized for its expected period of performance. Currently, enough compatibility to preclude disastrous reactions should be readily achievable through the use of existing sealing material. Ensuring this requires identifying and evaluating potential long-term chemical and mechanical interactions between the plug and its host environment, particularly with regard to reducing plug effectiveness as a barrier to fluid flow.

4.3. Multiple Plug Design

A multiple plug design is envisioned for the WIPP to ensure the effectiveness of sufficient redundant barriers at all times. A multiple design reflects (1) the function of the plug, (2) the time bounds of plug effectiveness, and (3) the location of the plug.

4.3.1. Function

The most credible mechanism for releasing radionuclides to the biosphere is groundwater. The primary function of the seal system is therefore to limit the flow of water in, through, and out of the repository. Some materials, such as clay, that can be used in plugs have the capability to sorb or retain certain radionuclides. A secondary function of the plug system, then, can be to act as a radionuclide sorptive barrier or getter. A further function of some plug components is to reduce the amount of salt creep required for closure and therefore the time in which it is completed.

4.3.2. Time

Owing to possible geochemical and mechanical interactions, confidence in a cementitious seal will be greatest for a limited time. Studies of ancient cements (Roy and Langton, 1982; Malinowski, 1981) lead us to believe this time may be about 1000 yr or more. Conversely, a backfill that densifies from the creep closure of an opening in salt should become increasingly effective as a fluid barrier with time. A design should recognize these differences to ensure continuous effectiveness of the overall system.

4.3.3. Location

The plug designs should strive for compatibility with the host environment to achieve maximum long-term stability. As penetrations pass through various bulk formations, the plugs should be designed for compatibility with their different geologic environments.

4.4. Plug Length

The design of the length of plugs for the WIPP may be based on or referenced to plug lengths that have demonstrated adequate functional properties. These required lengths may not be large, as suggested by the BCT (Christensen and Peterson, 1981). Plugs could then be designed as multiples of these reference-unit plug lengths. Such design would allow maximum flexibility (1) to accommodate (small) zones that might require plugs with specific functions, (2) to quantify the degree of redundancy of a design, and (3) to minimize unnecessary costs.

4.5. Flow Paths

Four potential flow paths are associated with a sealed penetration:

- The intact formation
- That part of the formation surrounding the penetration damaged by the excavation of the penetration (referred to as the "disturbed zone")
- The seal/rock interface
- The seal material itself.

4.5.1. Intact Formation

The WIPP is to be constructed in a geologic formation of primarily (~90%) halite. Laboratory measurements (Sutherland and Cave, 1979; Cooley and Butters, 1979; Black, Newton, and Shukla, 1983) indicate a permeability of $<1 \times 10^{-7}$ D. Clay seams, and other seams, may have permeabilities differing from that of halite, particularly near the excavation. Testing of 100-ft(30.5-m) intervals in the Salado (which will necessarily be comprised of all formation components in addition to halite) indicates permeabilities of $\sim 1 \times 10^{-5}$ D (Peterson et al, 1981). Besides the repository horizon, penetrations exist through formations above and below the Salado. The Castile, below, and the Rustler, above, both include bedded anhydrite and halite. Field and laboratory tests indicate that the permeability of intact anhydrite is comparable to that of halite (Peterson et al, 1981; Lambert and Mercer, 1977). While the Rustler may contain intervals that transmit water horizontally, a large degree of vertical isolation in various intervals has been demonstrated (Barr, Miller, and Gonzales, 1983). This isolation is possibly attributable to the interbeds of halite and anhydrite.

4.5.2. Disturbed Zone

The disturbed zone is generally thought of as a zone surrounding an opening in rock whose physical characteristics differ from those of the virgin formation. The potential for increased permeability of this zone is of fundamental concern to the Plugging and Sealing Program. The disturbed zone results primarily from (1) energy imparted to the rock surrounding an opening during excavation, and/or (2) the redistribution of natural stresses and resultant strains from excavating an opening.

4.5.3. Seal/Rock Interface

The seal/rock interface has been identified as the major flow path in laboratory (Gulick, Boa, and Buck, 1980) and field (Christensen and Peterson, 1981) tests on cement-based borehole plugs in anhydrite. The

seal/rock interface has been characterized as a region where the microstructure approximates a porous medium, not as a medium with a small number of fractures (Christensen and Peterson, 1981). (A physically poor bond, or dissolution along the interface would tend to create interfaces more similar to discrete fractures. More measurements are required to characterize the seal/rock interface.) The thickness of the interface zone, estimated at 0.2 in. (0.5 cm) for the borehole plug in the BCT, may be largely independent of the size of the opening and therefore may not be significantly greater for a cementitious shaft plug than for a borehole plug (Kelsall, Case, and Chabannes, 1982). Seal/rock interfaces for materials other than cement have not yet been characterized. However, the hydraulic conductivity of the interface may not be as significant for a plug that will chemically bond to the rock (as perhaps a salt backfill in an opening in salt may) or for a plug such as sodium bentonite that exerts a large swelling pressure.

4.5.4. Seal Material

The most obvious flow path is through the seal or plug material itself. Cement-based plugs have permeabilities restricted to the microdarcy range in both laboratory (Gulick, Boa, and Buck, 1980) and field (Christensen and Peterson, 1981) tests on borehole plugs. Laboratory measurements with various combinations of bentonite and other materials indicate permeabilities in the submicrodarcy range for these compacted materials (Peterson and Kelkar, 1983).

While materials exist that have very low permeabilities in laboratory tests, it is not obvious that these materials can be emplaced and retain their low permeabilities over an extended period of time. Horizontal emplacement, where gravity works against the roof/seal contact, may be particularly difficult. Remote emplacement, as in boreholes, also poses special problems such as assurance of complete filling of the void.

5. Sealing Design Concepts

The concepts presented in this report for sealing penetrations associated with the WIPP are derived in large part from previous studies (Christensen and Hunter, 1979; Hunter, 1980; Hunter, 1982; Christensen, Lambert, and Gulick, 1982; Kelsall et al, 1982; Daemen et al, 1983). These concepts and designs are only preliminary and as such are subject to change. Detailed designs, although expected to be uncomplicated, must be deferred until more information crucial

to design is obtained. Such information includes materials properties, long-term stability, emplacement techniques, etc. These designs will be assessed to ensure they adequately protect public health and safety. Further, designs will be optimized with respect to location, thickness, etc, of sealing components to provide for the greatest practical degree of the long-term isolation of waste.

5.1. Vertical Penetrations

Vertical penetrations associated with the WIPP are boreholes and shafts. The concepts are similar for sealing both boreholes and shafts. All materials used for plugging a penetration (vertical or horizontal) should be as chemically and mechanically compatible with the host environment as possible. Because vertical penetrations will pass through fundamentally different strata, plugs compatible with the specific environment are desired. This suggests a modular plug design.

The basic concepts for plugging vertical penetrations at the WIPP are shown in Figure 6 (Christensen, Lambert, and Gulick, 1982). More specific designs for boreholes and shafts are given in Sections 5.1.2 and 5.1.3, respectively. Sealing concepts address two locations: (1) in the evaporites (Salado and Castile) and (2) in the formations above and below the evaporites. In the salt sections, sealing is directed toward reconstruction, which means returning the formation to its predisturbed state. Because reconstruction may not be required or possible, alternatives are being considered that are neutral with respect to the salt. In the water-bearing Rustler Formation above and the DMG below, sealing consists of precluding water from the evaporites, minimizing salt dissolution, and providing time for possible reconstitution of the natural-salt plugs.

To enhance long-term stability, the predominately salt formations (the Salado and perhaps portions of the Castile) will be plugged with salt-based material or material that is nonreactive to salt rock. Some plugging options may make reconstitution possible. Crushed-salt consolidation and in situ salt precipitation (Lambert, 1980c) could eventually return the salt formations to their predisturbed state. The salt formations can also be plugged with a salt-based grout or concrete such as the BCT 1-F grout that will reduce dissolution of the neighboring salt during setup and provide longer-term stability of the grout plug (Gulick, Boa, and Buck, 1980). While it will not return the formation to its predisturbed state, this grout was formulated to be neutral with respect to the host rock and has demonstrated very low permeabilities (Gulick, Boa, and Buck, 1980; Christensen and Peterson, 1981). Clays, because of their low permeabilities and

probable low reactivity with the salt, can be used either in fills or as separate components to serve as both fluid (Peterson and Kelkar, 1983) and chemical (Nowak, 1980) barriers.

Potential fluid-bearing zones exist above and below the repository horizon. The principal fluid-bearing zones *above* the repository are the Culebra and Magenta aquifers in the Rustler Formation. The Bell Canyon aquifer is the fluid-bearing zone *below* the repository horizon. To protect from dissolution, these fluid-bearing zones should be sealed off from the WIPP horizon and from the halites of the Salado and the Castile. Isolation is particularly critical if a crushed-salt fill that is vulnerable to flow and dissolution until it consolidates is used in the salt formations.

A CaSO_4 -based concrete would be compatible (Christensen, Lambert, and Gulick, 1982) with these predominately anhydrite formations. A freshwater grout such as the BCT 1-FF (Gulick, Boa, and Buck, 1980) could also be used over these intervals. The zone that requires sealing to provide isolation should extend into the salt to ensure isolating the Rustler-Salado and DMG-Castile contacts. This suggests a plug such as the BCT 1-F (Gulick, Boa, and Buck, 1980) grout that is compatible with the salt formation. Natural materials such as clays could also be included. Again, clays such as bentonite have potential as fluid flow (Peterson and Kelkar, 1983) and chemical (Nowak, 1980) barriers.

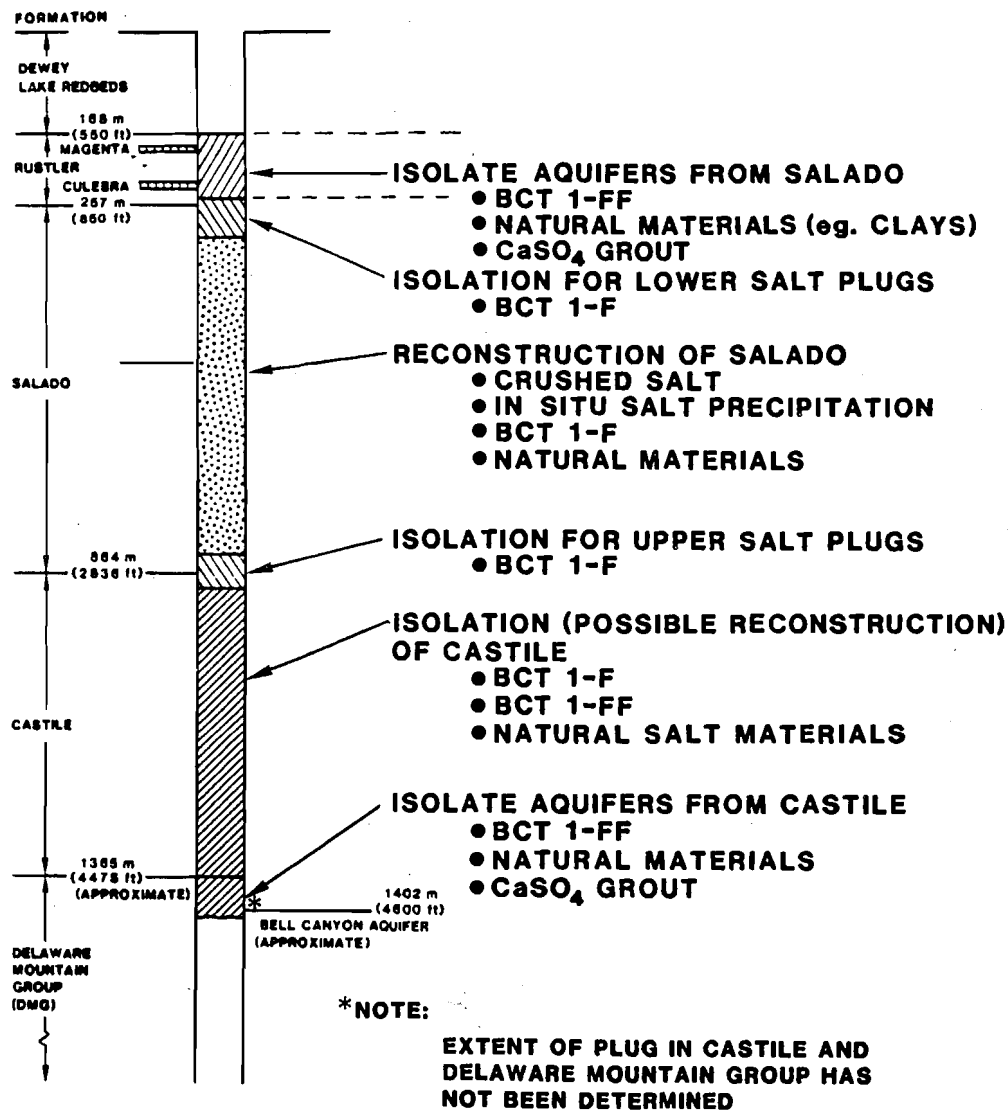


Figure 6. Concepts for Sealing Vertical Penetrations

5.1.1. Differences Between Shafts and Boreholes

Although both shafts and boreholes are vertical penetrations, they possess many differences with implications for sealing. For instance, their difference in size has many ramifications. The area of a plug increases as the diameter squared; thus flow through a plug also increases as the square of the diameter. Further, the volume of material to plug a 12-ft(3.7-m) shaft is more than 300 times greater than the volume needed to plug the same length of an 8-in.(20-cm) borehole. For cement-based plugs, this increased volume can mean significantly greater generation of heat during hydration (Daemen et al, 1983).

The thickness of the seal/rock interface may not increase with the increase in the diameter of the opening (Kelsall, Case, and Chabannes, 1982). This implies that the area and the flow of the interface increase linearly with the opening diameter, or about 20 times from typical borehole to shaft.

Both the size and the excavation method can result in a larger or more permeable zone surrounding a shaft. It is often speculated that the disturbed zone surrounding an excavation is proportional to the area of the opening (Kelsall, Case, and Chabannes, 1982). If so, the disturbed zone surrounding a penetration would vary as the square of the diameter of the opening, as would the flow through this zone. Thus the disturbed zone in a shaft may be much greater than that in a borehole because of the size of the opening. Evidence from laboratory (Mathis and Daemen, 1982; Lingle et al, 1981) and field (Christensen and Peterson, 1981) tests indicates only a small effect of the disturbed zone associated with boreholes. In addition, two of the shafts at the WIPP will be excavated in some part by blasting, which may cause some fracturing in the rock surrounding the shaft. Thus the excavation method may result in an increase in disturbed zone.

A positive facet associated with a shaft is that it allows for human access, permitting control and flexibility over host-rock preparation and actual emplacements (Kelsall and Shukla, 1980).

A further difference between boreholes and shafts relates to their use. Boreholes, except those left open for hydrologic testing or other monitoring, serve no current purpose for the WIPP. They can be plugged as soon as the technology permits. Shafts, on the other hand, are necessary for access during construction and operation of the facility and also during the required retrievability period. Thus it may not be practical to conduct extensive tests in the shaft before final sealing (Kelsall and Shukla, 1980).

5.1.2. Borehole Sealing

For plugging the WIPP boreholes, the current intent is to use Portland cement-based materials developed through the Plugging and Sealing Program. They have exhibited low permeability and high strength in laboratory and field tests, and our present knowledge provides no reason to doubt their adequacy for plugging applications. Two basic cement mixes were developed for application at the WIPP site. One incorporates a salt-saturated mix water (BCT 1-F), and one uses freshwater mix water BCT 1-FF.

Cement-based materials are preferred for their emplacement characteristics. Borehole plugging entails remote emplacement, and confidence is required to ensure that the plugging material completely fills the borehole volume and makes good contact with the borehole wall. This is particularly important in boreholes penetrating rock susceptible to substantial washouts (Christensen, Statler, and Peterson, 1980). Cement grouts have flow properties and established emplacement techniques that allow a good rock/plug contact.

Before plugging, existing casing should be removed where seals are to be emplaced. Over long periods of time, iron casing could corrode, leaving a more permeable conduit through the plug (Tremper, 1966; ASTM, 1976). Further, casing cement should be removed to reestablish contact of the host rock with the new plugging material. The BCT 1-F mix or a comparable cement should be placed in the salt zones to preclude dissolution of the host rock by the cement water. On the other hand, the freshwater mix, BCT 1-FF, is preferred in nonsalt zones because of its slightly better performance characteristics.

Plugging borehole B-25 was treated as an opportunity to use the best material and emplacement techniques and to exercise the Quality Assurance (QA)/construction interface in a borehole plugging operation to uncover potential areas of conflict (Christensen and Stormont, 1984). We used this activity to document the logistics, procedures, and decisions impacting a plugging operation that is subject to strict QA requirements. The only departure from a prototype plugging design for B-25 was to use sand in the upper portions of the borehole to facilitate reentry if necessary. Figure 7 shows the sealed wellbore B-25.

5.1.3. Shaft Sealing

Because of the large size of the shafts and their direct access between the Rustler aquifers and the WIPP excavations, greater emphasis will be placed on shaft seals than on boreholes. While cement grout alone may be the most appropriate seal in boreholes,

multiple sealing components will probably be used in the shafts. Major components of a possible shaft seal system (Figure 8) include the cap, base, seals (bulkheads), and fills.

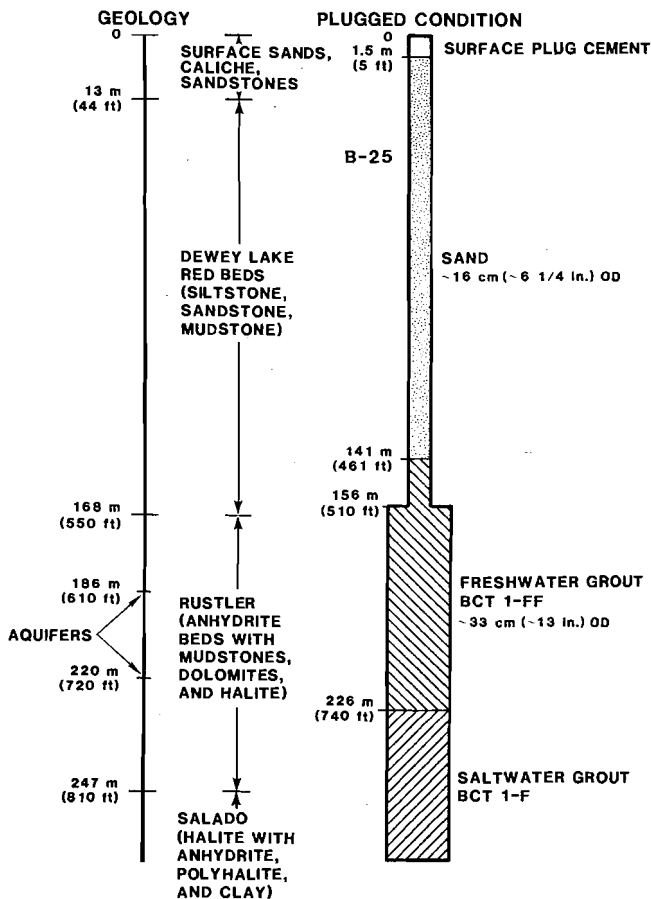


Figure 7. Plugged Condition and Associated Geology of the B-25 Borehole

A cap or cover will be placed over the shafts to prevent inflow of surface water and to serve as a permanent monument marking the shaft. The cap should withstand significant loads, such as vehicles passing over it. At the bottom of the shaft, a base is required to prevent substantial settlement or movement of the material in the shaft.

Shaft seals are required at potential fluid-producing zones to exclude water from the shaft. These zones are tentatively identified as the Magenta and Culebra aquifers and the Rustler-Salado contact. The seals will probably be composed primarily of concrete. Clay may be included to greatly reduce

the overall permeability while greatly increasing the travel time of water in the bulkheads. The length of the seals must be designed for structural and leakage considerations. Field experience has shown that the length required to prevent leakage in a cement-based plug is greater than that required for structural considerations (Garrett and Pitt, 1958; Garrett and Pitt, 1961). The design of the seal must also consider mechanical and geochemical interactions that may reduce long-term stability of such a system. Considerations include the stresses and strains induced in the formation and the plug from the geometric and material properties of the plug, and the potential for and implications of detrimental chemical reactions.

The design of the seals for shafts (and tunnels) may include keying the seals into the host rock. Examples include wedge keys, dual wedge keys, and cutoff collars (Chabannes, Stephenson, and Ellison, 1980). These keys are purported to provide increased structural support, to reduce the disturbed zone, and to increase the potential flow path along the interface. However, extensive keys may not be desirable from other perspectives. The required construction would present operational problems, and would be expensive, and the keys or angled bearing surfaces may induce undesirable stress concentrations in the rock near the loaded plug end (Daemen, 1983). Substantial keys require excavation that may just extend the disturbed zone farther radially into the formation. This would in fact *increase* the volume of material disturbed by the excavation. Further, extensive keys may not be necessary; the need for structural support for overlying fill is not obvious. Fills tend naturally to "arch" or to transfer vertical loads to the surrounding host rock (National Coal Board, 1982). Cylindrical borehole plugs <6 in. (15 cm) long emplaced in anhydrite (Gulick, Boa, and Buck, 1980), granite, and basalt (Stormont and Daemen, 1983) have resisted axial pressures >1000 psi (6.9 MPa). Experience in deep South African mines indicates the effectiveness of simple cylindrical plugs in severely restricting flow, particularly if the concrete-rock interface is pressure-grouted (Garrett and Pitt, 1958; Garrett and Pitt, 1961). Interface grouting may also reduce detrimental tensile stresses in the plugs (Stormont and Daemen, 1983). Further study culminating in field tests is required before determining the advisability of keying and/or interface grouting.

Grouting the aquifers can also be considered as a method of diverting groundwater from the shaft area. If proved necessary by monitoring the inflow into the shafts, this grouting could be cement-based or possibly a bentonite slurry (Meyer and Howard, 1983).

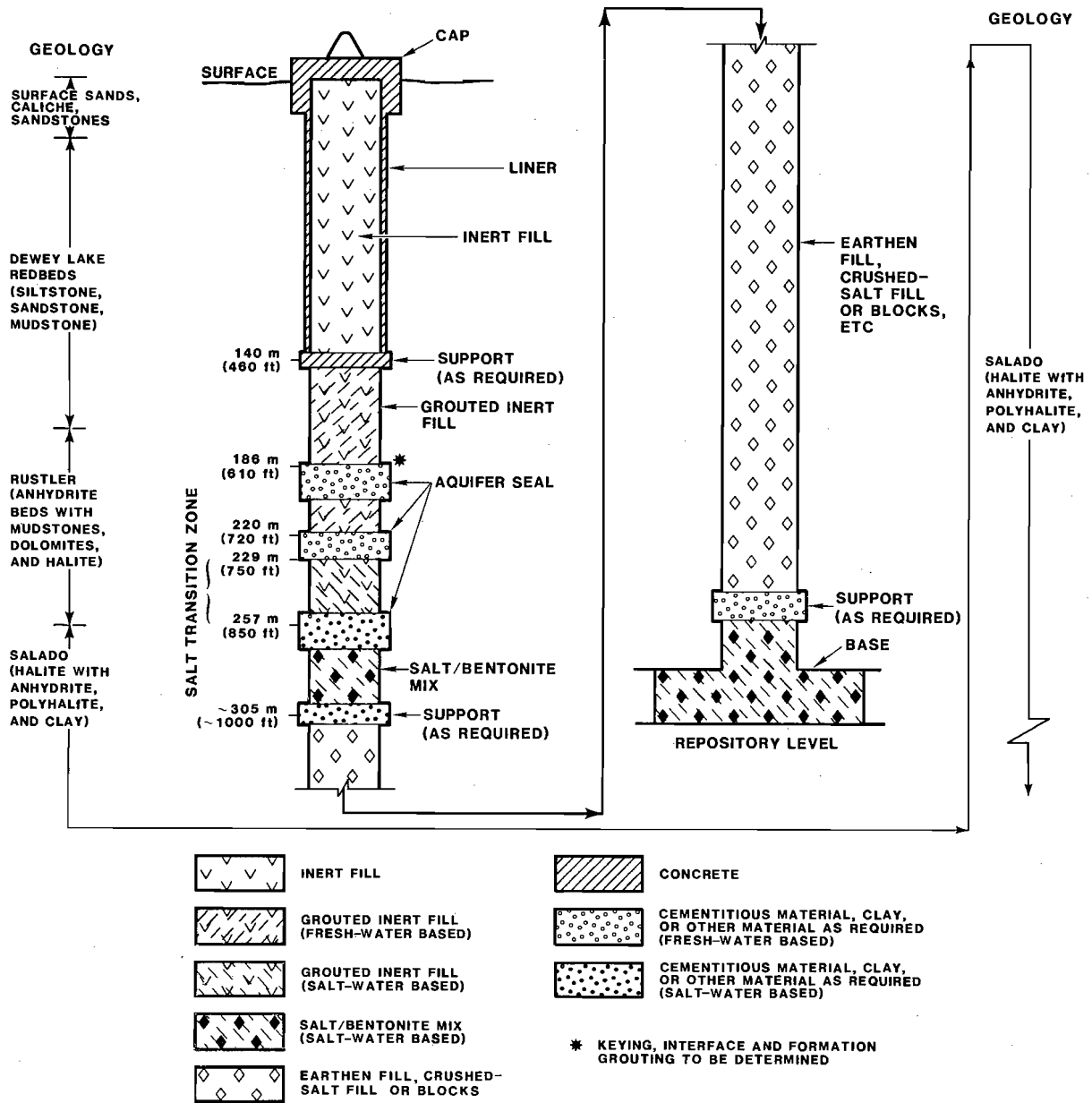


Figure 8. Preliminary Shaft Sealing Concepts

The steel liners in the construction and salt-handling shaft extend just beyond the top of the salt. Concrete liners are planned in the other two shafts. Portions of these liners must be removed at critical intervals to assure acceptable sealing, unless testing shows this is unnecessary. The performance of existing liners and keys will be evaluated in part by examining data from instrumentation (mainly piezometers) in the shafts. This information on liner and key performance is important because

- the existing liners and keys, or portions thereof, may be used for eventually sealing the WIPP

- it provides a baseline for the effectiveness of a concrete structure to restrict flow at the critical rock-liner or key interface
- it allows evaluating the performance of somewhat different configurations (simple cylinder vs key, performance vs shaft construction method, etc).

Much of this type of information will be extrapolated to the design of bulkhead-type seals for the shafts.

The fills used in the shaft can be comprised of many materials. The fill from the shaft cover to ~500 ft (152 m) from the surface need not have especially low permeability because these formations are themselves relatively permeable. The fills between the various seals need to possess low plug and interface permeability and must not settle significantly. Grouting preplaced fill aggregate may reduce settlement, provide structural support, and decrease permeability. The fill in the salt zone could consist of crushed-salt fill, salt bricks, salt aggregate, and salt-based grout if water-bearing strata are isolated enough to preclude significant salt dissolution. Using salt-based fills depends on their not becoming preferential flow paths. Even then, salt-based fills may be appropriate only near the base of the shaft, depending on (1) the stress conditions required to reconsolidate the salt and (2) the quantity of water and length of time for water to flow through the shaft seals. Backfills composed of natural materials such as clays will also be considered. Some support may be required for the fill.

5.2. Horizontal Penetrations

Horizontal *penetrations* to be sealed will be associated with the repository as access drifts and storage rooms; horizontal *sealing* will be in the form of bulkheads and fills. Horizontal penetrations differ from vertical penetrations in that

- the host formation is entirely within the Salado Formation (primarily halite)
- plug emplacement near the roof of drifts will demand special consideration
- the plugs will be closer to the waste (radio-nuclide concentrations)
- the effective permeability of concern may be dominated by disturbed-zone and horizontal interbeds of high permeability.

As with vertical penetrations, compatibility between the plug and its environment is desirable for long-term chemical and mechanical stability.

The cross-sectional area of tunnels is of the same magnitude as that of shafts. Therefore, the potential size effects identified for shafts apply to plugging tunnels. However, the horizontal geometry may bring the horizontal bedding and associated effects into more prominent consideration.

The current concept calls for multiple component bulkheads in main access tunnels and the submain entries to the panel rooms (Figure 9). These plugs will isolate the disposal area from the shafts, and panels from each other. Seal locations will remain unspecified pending determination of the exact location of the waste in the WIPP.

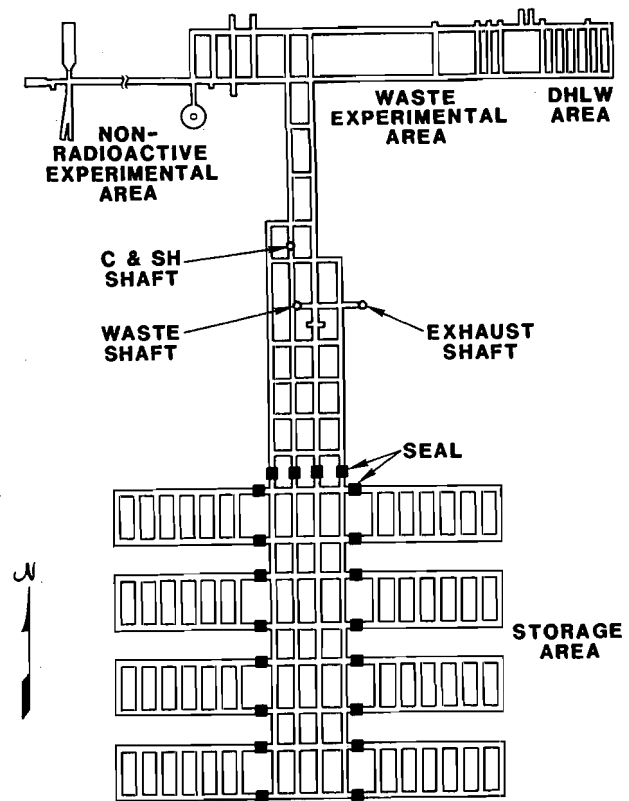


Figure 9. Tentative Locations of Seals in the WIPP

Figure 10 illustrates one possible multiple seal. This seal is symmetric about the center for redundancy and for restricting flow in either direction by similar means. The multiple plug shown includes cement-based, salt-brick, and compacted bentonite components. The design, including the lengths of individual components, cannot be specified until long-term leakage and structural considerations are addressed. Also to be considered are the chemical and thermodynamic compatibility of sandwiching three different materials together. It may be advantageous to place thin, inert separators between components to minimize chemical and thermodynamic reactions.

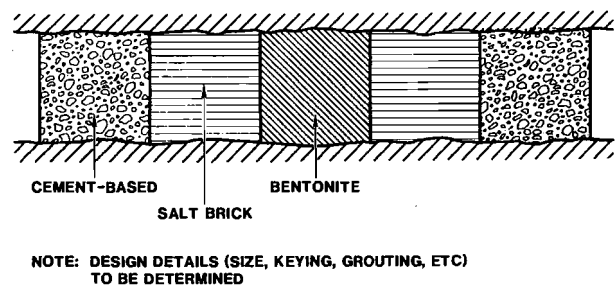


Figure 10. Preliminary Multiple Seal Concept

The cement-based bulkheads will provide immediate, short-term (and possibly long-term) fluid barriers. These bulkheads will isolate the interior components, allowing them to compact under pressures exerted by the creep closure of the opening. Concrete-rock interface grouting may be appropriate, as discussed in the previous section.

Salt bulkheads constructed with salt bricks are the next component in the modular design. If the salt bulkhead consolidates from the pressure of the closing tunnel into a mass with properties like those of intact salt, the tunnel would no longer be a path of preferential flow or dissolution. The emplaced density should be as great as possible to minimize the time required for reconsolidation. This may require some preparation of the granular salt, particularly wetting, before forming the bricks. A mortar of salt-based grout or a bentonite-based slurry could be used between the bricks and at the roof to ensure an adequate seal.

A core of bentonite, or a bentonite-based mix, is located in the center of the multiple component bulkhead. This core could be an in-place compacted bentonite or a bulkhead of bentonite bricks. A bentonite slurry could be used between the bricks and at the roof to ensure a proper seal. Compacted bentonite has a low permeability ($<10^{-6}$ D) and the ability to retain certain radionuclides. Thus it is both a fluid and chemical barrier. If the bentonite is confined between the salt bulkheads, the swelling pressures induced by contact with water tend to increase the interface pressure and to decrease the permeability of the interface. The bentonite can be considered an effective immediate barrier and would probably be as (or more) effective as its density increases with time from room closure.

Proper design of these bulkheads will require obtaining location-specific information. The host rock, not the plug, may be the primary design consideration (Garrett and Pitt, 1961). Clearly, all broken and loose rock surrounding the excavation must be removed before bulkhead installation, but the extent of this secondary excavation is not yet obvious. For example, if a laterally persistent clay seam is immediately above or below the opening, it may be best to enlarge the opening to remove the seam. If the extent of the disturbed zone surrounding a tunnel increases with time, then increasing the size of the opening immediately before bulkhead installation may reduce the size and effect of such a zone. On the other hand, substantial keying may be detrimental, as discussed in Section 5.2.2.

The fills placed in rooms *not* containing waste will likely be composed primarily of granular salt. The fundamental reason is that the pressures exerted by

the closing of the excavation from salt creep may eventually return the fill to a condition comparable to that of intact salt. Granular salt will also be plentiful and available onsite from the WIPP construction. The operational procedures will be influenced by the treatment (crushing, sizing, wetting) required to produce an optimum fill.

Adding other materials such as clays to the fill will be considered for rooms containing waste. Including clays may substantially reduce the hydraulic conductivity of the fill before significant consolidation (Peterson and Kelkar, 1983) and may also provide sorptive capabilities.

In rooms containing TRU wastes, a fill such as crushed salt will be placed over the containers to reduce the fire hazard. At the ceiling an initial gap of 1 to 2 ft (0.3 to 0.6 m) will permit ventilation. A fill such as crushed salt alone placed over waste is not considered a significant barrier in the sealing strategy because it will not provide any fluid or chemical barrier in the short or long term. The WIPP Plugging and Sealing Program considers bulkheads at the storage area entries to be engineered barriers. Tailored fills in the waste room will be evaluated for added conservatism with respect to the EPA regulations for engineered barriers.

We do not presently envision any horizontal boreholes requiring sealing. If the need arises, existing techniques will be used for grouting horizontal instrument boreholes at the WIPP.

6. Issues and Activities of the Plugging and Sealing Program

6.1. Introduction

The WIPP Plugging and Sealing Program seeks to identify and resolve sealing issues for the WIPP through integrated laboratory, field, and modeling efforts. The general concepts and options identified earlier in this document will be fully evaluated through these studies. The knowledge gained by these investigations will be incorporated into assessments of various designs and scenarios to evaluate and then aid in choosing the sealing design. Much information will be gathered by maintaining close interfaces with other experimental programs such as the Thermal/Structural Interaction Program and the Waste Package Performance Program (Matalucci et al, 1982). This section identifies major issues (unresolved

technical concerns and information needs) and describes some activities and techniques for resolving these issues. If any new issues develop due to accumulated knowledge and experience, they will be addressed in Plugging and Sealing Program Test Plans. Some issues and activities are presented here in greater detail than others because more is known in certain areas at the present.

Test plans will be written for in situ tests. These plans will include the purpose, background objectives, and scope of the test, as well as personnel responsibilities, schedules, and QA management. WIPP QA procedures (SNL, Waste Management Tech., 1983a) will ensure proper project and peer review and documentation of test activities.

The WIPP Plugging and Sealing Program is responsible for developing the design basis and criteria for sealing the WIPP facility. This includes conducting all relevant R&D to establish a data base on rock, seal material, and design performance, and to develop seal system performance requirements to satisfy pertinent EPA regulations. The R&D activities can be categorized as follows:

- Formation/Facility Characterization
- Materials Development
- Geochemical Interactions
- Mechanical Interactions
- In Situ Seal Performance
- Seal System Evaluation

Ongoing characterization of the geologic, mechanical, and hydrologic properties of the WIPP formations is required as input to (1) selecting and evaluating materials that are compatible with the host rock, (2) aiding in seal design, and (3) developing seal system performance requirements. The materials selection and evaluation process strives to develop materials that are compatible with the host rock and that also possess desirable properties. Long-term stability, both chemical and mechanical, will be evaluated by using predictive models developed on the bases of formation and seal materials characterization and validated by laboratory and field tests. Small-to-large-scale tests will be performed to verify preliminary designs, to evaluate emplacement technology, and to determine in situ seal performance. Seal system performance requirements or criteria will be developed by modeling the effect of the seal system on attaining allowable isotope concentrations. Designs (materials, emplacement techniques, etc) that will meet the stipulated performance will be determined by evaluating all the R&D on seal performance.

The following sections contain issues and activities headings. The current state of knowledge, unresolved technical concerns, and information needs are

presented under issues. Planned and possible tests, techniques, and measurements for resolving these issues are described under activities. Test plans will be written for major investigations.

6.2. Formation and Repository Characterization

6.2.1. Introduction

Knowledge of formation properties and knowledge of properties that change as a result of excavating the repository are important inputs for performance evaluations and plug design. Mechanical/thermal, geochemical, and hydrologic *properties* are of interest. The principal *formations* of interest include the repository horizon, and water-bearing zones above and below the horizon. Repository development significantly affects relevant in situ properties, and the extent and nature of this effect must also be known.

Understanding the mechanical/thermal response of the formation to the excavation and to the heat produced by radioactive waste is a primary objective of the Thermal/Structural Interactions (TSI) Program (Matalucci et al, 1982). Of particular interest to the Plugging and Sealing Program is the rate of creep closure of openings. This rate will determine the time and degree of expected consolidation of room/drift fill, and the mechanical behavior of a seal in a drift or shaft. The initiation, propagation, and healing of fractures is another common concern of both the TSI and Plugging and Sealing Programs. These fractures could result in preferential flow paths, perhaps effectively bypassing seals. The conditions at which fractures form, the extent to which they propagate, the conditions at which they heal, and the permeability of healed fractures must be known in order to make long-term assessments of sealing effectiveness.

A report by Powers et al (1978) contains hydrologic and chemical characteristics of the WIPP site. These characteristics are periodically updated as part of the WIPP Geotechnical Studies Program (SNL, Waste Management Tech, 1983b). Knowing hydrologic properties of the water-bearing strata is essential to accurately assessing sealing designs. Knowledge of the chemical composition of water and rock is needed to assess the long-term geochemical stability of the plug, host rock, and water system.

6.2.2. Formation Permeability

6.2.2.1. Issues

While it is evident that undisturbed intact rock salt has a very low permeability (Sutherland and

Cave, 1979; Cooley and Butters, 1979; Black, Newton, and Shukla, 1983), the presence of interbeds and the effects of excavation may result in an effective permeability of the repository horizon that is greater than that of intact salt. Knowledge of this effective permeability is essential for all sealing designs.

The inherent complication in obtaining a measurement of the permeability of the gross formation is decoupling the contributions of all the components. Because the Salado is a bedded deposit, permeabilities may be anisotropic with respect to the vertical and horizontal directions. The presence of interbeds, such as clay seams, could result in higher horizontal than vertical permeability. The disturbed zone in the rock surrounding the excavation could contribute to the flow around a sealed excavation. All investigations into the permeability of the formation will be evaluated to aid in thoroughly understanding the contributions of the formation and repository components and their interactions that result in the permeability of the gross formation.

It is possible that the permeability of salt to water decreases with time. Tests of the permeability of the interface between salt crystals indicated a decrease in permeability with time, attributable to a reduction in width of the interface from pressure solutioning (Gilpatrick et al, 1982). Katz and Coats (1968) state, "One gains the impression that . . . liquid brine pressure causes any permeability channels in the rock salt to heal and reduce to very low values compared to the dry salt."

To date, there are limited data on in situ permeability of the WIPP horizon. A measurement made over a 100-ft(30-m) interval in the Salado indicates a repository horizon permeability in the range 1×10^{-5} D (Peterson et al, 1981), attributable primarily to horizontal flow. This measurement, while made in situ, involves a very small volume of the formation and does not include the effects of openings of the size anticipated for the repository. Further, although the measurement was made in the Salado, it was not made within the bounds of the proposed repository. An in situ measurement of domal salt permeability (Blankenship and Stickney, 1983) reported submicrodarcy values.

The following conclusions are drawn from many laboratory permeability tests on rock core from the WIPP site (Sutherland and Cave, 1979; Cooley and Butters, 1979; Black, Newton, and Shukla, 1983):

- There are no apparent variations in permeability for different rock types typical of the WIPP horizon, excluding clay/anhydrite seams

- There are no apparent variations in permeability for cores taken from different orientations (horizontal, vertical up, or vertical down)
- Sample removal increases permeability; this effect is reduced as the sample "heals" under triaxial stress states approximating the in situ condition
- After this healing, samples have a permeability approaching $0.01 \mu\text{D}$.

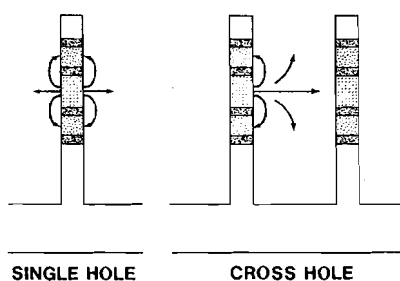
6.2.2.2. Activities

Various permeability measurements can be made to aid in understanding the permeability of the repository horizon. These include borehole and bulk in situ measurements and laboratory measurements. Borehole gas permeability measurements conducted in the WIPP in 1984 should contribute significantly to the current level of knowledge and point toward appropriate future measurements.

In Situ Permeability Tests in Boreholes. This test is to be performed in boreholes in the WIPP facility. This test (or portions of it) will begin in 1984 depending on the state of excavation and instrumentation of the experimental areas (Peterson and Stormont, 1984).

The test can be conducted in single-hole or cross-hole configurations (Figure 11). Pressurized gas, or possibly a liquid such as brine, will be used to obtain flow data. In the cross-hole configuration, the test provides for a fluid source of known pressure, and measures pressure buildup with time in the sink hole. The rates can then be compared to porous and crack flow models to determine the flow characteristics in the medium tested. In the single-hole configuration, gas at known conditions is injected into the formation, and pressures are monitored to determine flow characteristics. Guarded straddle packers (patented by S-Cubed) will be used to determine radial and tangential flow from the borehole and thus provide less ambiguous permeability data (Peterson, 1983). Test dimensions and locations will be varied to try to identify and decouple the effects of vertical and horizontal permeabilities, interbeds, and disturbances caused by excavations.

Permeability Test of the Bulk or Gross Formation. This test is similar to the In Situ Borehole Permeability Test except that the test will be conducted in drifts, not boreholes. The surface area tested in a drift is much greater than in a borehole, thereby providing a result more representative of the entire formation.



Permeability Measurements in the Laboratory. Many permeability measurements have been made in the laboratory on cores of rock representative of the WIPP horizon (Sutherland and Cave, 1979; Cooley and Butters, 1979; Black, Newton, and Shukla, 1983). Inherent limitations of these measurements (sampling damage, small sample volume, not in situ conditions) suggest that field measurements may provide more information on permeability of the in situ formation. However, further permeability measurements will be made in the laboratory to try to understand the influence of specific variables. For example, tests will be made in 1985 on the effects of water as the permeant.

Permeability Measurements in Shafts. Permeability measurements may be made in one or more shafts to determine representative permeability values at strategic locations. These measurements may indicate the effects of construction method on permeability (construction and salt-handling shaft was bored, the exhaust and waste shafts were blasted in part). Because of the unique working conditions in the shafts (working from a conveyance in a small area), instrumentation and techniques used in WIPP horizon investigations may not be appropriate.

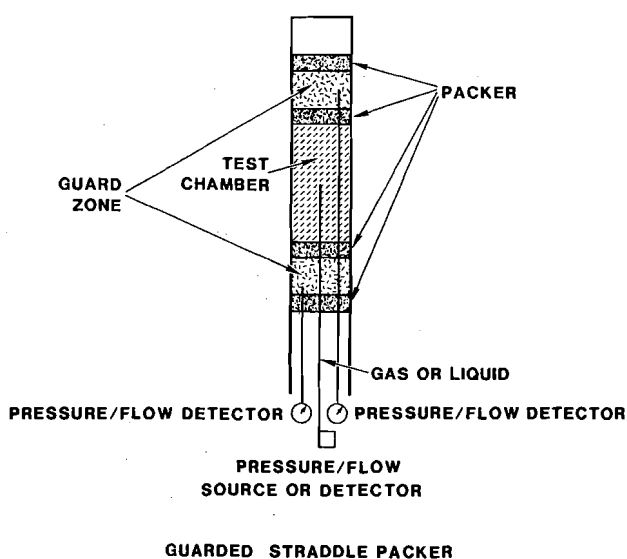


Figure 11. In Situ Borehole Permeability Configuration and Guarded Straddle Packer (patented by S-Cubed under contract E512-08800 with the Office of Nuclear Waste Isolation)

A tracer gas is released into the test region in a sealed drift at measured rates and conditions. Tracer dilution techniques are used to measure the flow past the pressure barrier and gas surface seal. The flow into the formation is the difference between the gas released and the gas detected in the tunnel beyond the barriers. Multidimensional analysis is then used to estimate the flow in the bulk formation and the disturbed zone. Further information may be gained if the tunnel tested is located near other tunnels that could detect the tracer gas. A drawback to this test is the potential for contaminating the formation with tracer gas, thereby obscuring future test results. This technique could also be used to test bulkheads and backfills by replacing the gas seal with backfill or bulkhead material.

6.2.3. Disturbed Zone Characterization

6.2.3.1. Issues

The disturbed zone is the portion of the formation surrounding an excavation whose properties have been altered because of (1) energy imparted to this zone during excavation, and (2) the redistribution of stresses surrounding the opening. The disturbed zone manifests itself as fractures or by stress-relief loosening of the crystal interfaces. A fundamental concern with regard to the Plugging and Sealing Program is the potential for increased permeability in this zone. The extent and nature of the disturbed zone are as yet largely unknown.

Although blasting techniques used in shaft construction may produce more initial fractures than do boring methods, these fractures are not expected to have a detrimental effect on sealing the WIPP. The fractures occurring in salt may close and seal by creep deformation of the salt (Costin and Wawersik, 1980). Because fractures already exist in the Rustler aquifers and will provide flow paths regardless of the excavation technique, the disturbed zone is of less consequence in these overlying formations (Weart, 1983). The continuous mining machines used for excavation at the WIPP minimize rock damage and fractures in the rock surrounding the excavation.

Redistribution of natural stresses caused by the excavation, and the creep closure of the opening induced by these stresses may result in some fractures. A few examples of vertical fracturing in pillars at room intersections have been observed after the excavation has been open for ~6 months (US DOE, 1984).

Besides fractures, the disturbed zone may also include a volume of rock surrounding an opening with increased permeability caused by loosened crystal boundaries resulting from a stress state different from the assumed in situ hydrostatic stress state. Some researchers (Kelsall, Case, and Chabannes, 1982; Lai, 1971) contend that this dependency of permeability on confining stress will cause permeability to decrease up to 5 orders of magnitude, with an increase in confining stress from 0 to 2000 psi (13.8 MPa). These laboratory results are likely to be masked by damage from sampling. Other investigations (Sutherland and Cave, 1979; Cooley and Butters, 1979; Black, Newton, and Shukla, 1983) compensated for the sampling damage by first subjecting the salt to its assumed original stress state. This appears to "heal" the sample. Once healed, the permeabilities of these samples did not vary significantly for wide ranges of applied stresses. These results indicate that the healing process is irreversible. That is, once the effects of sampling are removed from a specimen, the permeability is not strongly dependent on confining or deviatoric stresses.

6.2.3.2. Activities

Because theoretical and laboratory investigations remain inconclusive and no resolution appears imminent, the extent and impact of the disturbed zone must be established as it exists in situ at the WIPP. Emphasis will therefore be on field measurements.

The velocity and attenuation of an elastic wave are related to the properties of the rock and the material in pore spaces (inclusions, fractures, and granular boundaries) (Wyllie, Gregory, and Garner, 1958). Because the disturbed zone in salt is thought to be partly a zone where crystal boundaries are loosened (Kelsall, Case, and Chabannes, 1982), an ultrasonic elastic wave traveling in the disturbed zone may have different characteristics from one traveling in undisturbed rock. If ultrasonic measurements are made from boreholes extending from the rib of an excavation into the formation, a profile can be determined of the velocity and attenuation response with depth from the opening. This type of measurement could provide information about the extent and nature of the disturbed zone.

A preliminary series of measurements as described above were made in 1983 and 1984 at the WIPP. The technique appears promising in defining a zone adjacent to the excavation with significantly altered ultrasonic wave characteristics. Work is ongoing toward improving the field equipment and data evaluation techniques.

A program was initiated to evaluate the feasibility of correlating the results of permeability and ultrasonic measurements in rock salt (Stormont, 1984). To some degree, both permeability and ultrasonic measurements may describe the pore volume (microcracks, grain boundaries, etc) characteristics of a volume of rock salt. Permeability and ultrasonic measurements will be made under the same laboratory conditions. In situ borehole gas permeability measurements may be made near or in a setting similar to that in which in situ ultrasonics measurements were made. Comparing measurements and determining the corresponding rock and pore volume conditions may indicate a possible correlation.

If a relationship could be established between permeability and ultrasonic measurements, it would reduce or eliminate further expensive, time-consuming, and difficult in situ permeability measurements.

The Permeability Test of In Situ Boreholes and the Permeability Test of Gross Formation (see Section 6.2.2.2) will also provide information on characteristics of the disturbed zone.

6.2.4. Interbed Characterization/Gas Occurrence

6.2.4.1. Issues

The repository horizon is not comprised of a monolith of salt, but of layers of salt, anhydrite, polyhalite, and clay zones. While much of the bedding may not alter the properties of the gross formation, some layers (often referred to as interbeds) possess significantly different properties.

Polyhalite and anhydrite have different material properties from those of halite and do not exhibit as pronounced time-dependent creep deformation. These differences in mechanical properties and behavior may have implications for the Plugging and Sealing Program. The TSI Program (Matalucci et al, 1982) and the WIPP Geotechnical Studies Program are investigating the mechanical behavior of these interbeds as well as the mechanical properties of clay seams.

Most current concern centers on characterizing clay seams. Many horizontal clay seams or partings exist near the WIPP horizon. Twelve distinct clay seams within 100 ft (30 m) vertically of the repository horizon are included in the current WIPP reference stratigraphy (Krieg, 1984). The mechanical and hydrologic properties are largely unknown at this time. From the perspective of the Plugging and Sealing Program, these clay seams merit study because (1) they may represent the highest permeability zones near the WIPP excavation, and (2) some of these beds may produce gas and/or liquid when penetrated.

The clay seams are horizontal and represent a discontinuity between beds. The stress relief produced from the excavation may allow these seams to separate somewhat. If the clay seam aperture becomes large enough, and if the seams extend far enough laterally, the seam could appear as a significant discontinuity providing a flow path over a large portion of the excavation.

Gases and liquids observed in boreholes may originate from clay seams (US DOE, 1983). The exact origin of the gas in situ is unknown, however. The clay seams may represent a source or a trap of gas, or both. (Another possibility is that the gas may be contained in fractured units adjacent to the clay seams.) Common mining practice in the Carlsbad potash district calls for penetrating clay seams with gas-relief holes. Venting gas into a sealed room could pressurize the room to some degree and reduce closure rates of the room depending on the volume and pressure of the gas. However, this appears unlikely based on previous calculations (SNL, 1979). Of perhaps more concern, vertical probe holes or other connections such as fractures that intersect horizontal clay seams could provide a flow path for bypassing the barriers of the geologic formation and the engineered seals.

Thus, the permeability and connectivity of various interbeds and the gas reservoir pressure and volume are characteristics of particular interest to the Plugging and Sealing Program.

6.2.4.2. Activities

Several *Borehole Interbed/Gas Tests* can be conducted in a single borehole to provide information on gas occurrences and interbed characterization. After a borehole encounters gas, usually in association with a clay seam, the gas-producing region can be isolated or shut in by using a special drill rig developed by Sandia National Laboratories (Christensen, 1981). An alternative is to remove the drill string and use packers to contain the gas; this procedure, however, may significantly deplete the gas reservoir. Once the

test interval is shut in, the gas pressure of the interval can be determined. After the initial pressure is determined, gas could be produced for a time, after which the interval would be shut in again. The reservoir volume could then be determined based on the initial and final pressures and the volume of gas produced (Peterson and Stormont, 1984). Another operation is to drill back into the gas reservoir or seam to allow using a television camera or other method to evaluate the geometry of any discrete void (Christensen, 1981).

An in situ Gas Testing Program (Torres, 1984) initiated in 1984 will provide information on the pressures, volumes, and connectivity of the gas-producing regions. These data will be important in determining plugging requirements.

If two boreholes are drilled through the same clay seam at some distance apart, the apparent permeability of the clay seam can be determined by an interference test (Peterson and Stormont, 1984). The procedure is to isolate the seam in both holes with packers and then to measure the pressure changes induced in one hole as a result of gas injection in the second. Connectivity of clay seams would be evaluated by pressure testing and using a cross-hole configuration. Flow path aperture could be determined through cross-hole tracer tests (Peterson and Stormont, 1984). These measurements may be made during the Permeability Test of In Situ Boreholes previously described (see Section 6.2.2.2). If warranted, these methods may be used on interbeds other than clay seams.

6.2.5. Fracture Characterization

6.2.5.1. Issues

Fractures in rock can provide significant conduits for fluid flow, allowing water to bypass the relatively impermeable natural formation. Discrete fracture flow is governed by a cubic law (Witherspoon et al, 1980) which states that the flow in a fracture is proportional to the third power of the fracture aperture. Thus fracture flow can be significant where an open fracture exists. Brine permeability of fractures in rock salt may decrease with time because of pressure solution and precipitation along the fracture.

The initiation, propagation, and healing of a fracture are intimately related to the stress history. The aperture size, which strongly controls flow, depends on the stress conditions for a deformable rock fracture. Anticipated stress distributions around an opening will initially tend to open circumferential or "onion-skin" fractures and to close radial fractures. Subsequent creep deformation may heal these fractures. These topics relating to fractures are being studied in the TSI Program (Matalucci et al, 1982).

At the facility level, several radial vertical tension fractures in the salt pillars at the room intersections have been observed. The widths of these fractures range from hairline to about 1/2 in. (1 cm) wide and extend an undetermined distance radially. Some of these fractures are apparently increasing in length with time. No gross bedding separations have been observed to date (US DOE, 1984).

6.2.5.2. Activities

Some fractures in the shafts and in the repository will be mapped during excavation. Periodic monitoring will reveal new fractures and will document the condition of previously recorded fractures. Attempts will be made to quantify the geometrical properties and other discernible features of the fractures. If fractures are numerous in the waste and exhaust shafts, which are to be excavated in part by blasting, core samples into the wall will be taken to determine radial extent of the fractures.

If warranted, cross-hole testing of fractures similar to that proposed for clay seams will be performed to measure connectivity and permeability of fractures. Ultrasonic borehole measurements may also provide information on fracture characteristics.

The Plugging and Sealing Program will stay abreast of the work supported by the TSI Program to characterize fractures. Laboratory and field investigations will eventually be incorporated into numerical and analytical methods that allow accurate prediction of the occurrence of fractures at the WIPP.

6.3. Materials Development

6.3.1. Introduction

Materials development for the Plugging and Sealing Program has been ongoing since 1975. Most of the development was for Portland cements as the principal material and technology was available for use (Gulick, Boa, and Buck, 1980). Development will continue for cement-based materials, as well as for other materials such as granular salt and bentonite-based backfills and bulkheads.

In developing materials, we will try to optimize desired properties (e.g., low permeability, high strength), while ensuring compatibility with the host environment. For this reason the development includes considerations of geochemical and mechanical long-term stability.

Materials development can be grouped into the following activities:

- Cement-based development
- Granular salt-fill development
- Tailored-fill development
- Block development
- Alternative materials development

Work on alternative materials has focused on salt precipitation. A laboratory technique to precipitate in situ salt and anhydrite has been developed (Lambert, 1980). Once the technique is perfected, the method will be field-tested at the WIPP.

6.3.2. Cementitious Materials

6.3.2.1 Issues

Desirable properties of cementitious seal materials include low permeability, low porosity, high density, high strength, expansive potential, isotropy, homogeneity, pumpability, adequate working time, stability, and durability (Gulick, Boa, and Buck, 1982). In particular, the longevity of these properties in the WIPP environment is of paramount importance to the seal design process. Much work has been done in developing cement-based materials for the WIPP Plugging and Sealing Program. Much of this work was done at the US Army Corp of Engineers Waterways Experiment Station (WES) Structures Laboratory with emphasis on determining what materials are compatible with the WIPP environment.

Lowering the ratio of water to cement generally reduces permeability and porosity and increases density and strength (Gulick, 1980; Gulick, Boa, and Buck, 1982). Reducing the water-to-cement ratio in grouts made with Portland cement products was achieved by using the coarser available grinds of cement and by using water reducers and retarders. Strength and durability are also increased when the amount of free calcium hydroxide is reduced. This can be done by adding siliceous or pozzolanic materials that react with the calcium hydroxide to form the more stable and durable calcium silicate hydrates (Gulick, 1980; Gulick, Boa, and Buck, 1982).

Expansive grouts were developed to improve the interface bond with the rock. The expansion is based on the formation of calcium aluminate phases such as ettringite (Gulick, Boa, and Buck, 1982). The expansion will improve the mechanical bond and should reduce plug movement and permeability, especially at the interface (Gulick, Boa, and Buck, 1982). Sulfate attack is resisted by developing cements low in tricalcium aluminate (Gulick, 1980).

Two mixes developed for the BCT (Gulick, Boa, and Buck, 1980) serve as the baseline formulations to date. These mixtures are the BCT 1-F *saltwater-based mix for rock salt* sections and the BCT 1-FF *freshwater-based mix for nonsalt* sections. Laboratory testing (Gulick, Boa, and Buck, 1980) on the bare grout, as well as the grout cast in anhydrite, supplemented the field test of a BCT 1-FF plug cured in situ (Christensen and Peterson, 1981). Modifications to the BCT 1-FF to enhance particular properties were identified and tested (Buck et al, 1983). Cementitious grouts developed specifically for the WIPP were emplaced in wellbores AEC-7 (the BCT) and B-25, and in the SPDV exploratory shaft liner.

6.3.2.2. Activities

Cementitious material development will continue at Waterways Experiment Station (WES). Developing and improving existing formulations will continue in 1984 and beyond. Granular WIPP rock salt will be evaluated for use in brine mix water as fines and in concrete as aggregates. The increased use of silica fume and sand will be investigated to promote stability and strength. State-of-the-art improvements to cement technology will be incorporated into existing grout formulations as they develop. Samples cast from the field pours are preserved for physical property and petrographic evaluations to indicate longevity of the cements (Burkes and Rhoderick, 1983). Testing samples from previous pours will continue periodically.

Concretes will be developed for both salt and nonsalt environments. The type, amount, and size of aggregate will be optimized. Grouts suitable for pressure grouting will be developed if needed. Calcium sulfate-based grouts will be considered for further evaluation. A grout or concrete with a deformability closer to that of salt may also be developed.

6.3.3. Granular Salt Consolidation and Permeability

6.3.3.1. Issues

If granular or crushed salt emplaced in drifts and shafts at the WIPP eventually consolidates into a mass equivalent to that of intact salt, penetrations will not be discernible from the surrounding formation and will therefore not be a preferential dissolution or flow path to water. Evidence of the long-term exclusion of groundwater and of the stability of the in situ salt beds (Clairborne and Gera, 1974) suggests that allowing nature to isolate the waste is superior to engineered isolation.

It has long been proposed that granular salt will reconsolidate into essentially intact salt. Recent laboratory investigations indicate that consolidation depends on particle size, moisture content, and stress level (Holcomb and Hannum, 1982; Shor, Baes, and Canonico, 1981). Calculations indicate that initial density greatly affects the time required for consolidation (Hunter, 1982, Kelsall et al, 1982). All the mechanisms governing consolidation are not yet clear. Consolidation in a moist environment appears to be considerably faster than under dry conditions, perhaps because of different rate-controlling mechanisms. Consolidation under *dry* conditions probably involves only mechanical processes; in a *brine* environment a process similar to sintering has been postulated (Shor, Baes, and Canonico, 1981).

Creep of consolidating granular salt appears to differ from creep of intact salt in that no steady-state rate is evident in the short-term tests conducted to date. Rather, the rate appears to decrease as a function of 1/time. A possible explanation is that, at a constant applied stress level, particles of salt compress together and their points of contact become larger. The stress at these points of contact then continually decreases; thus the creep rate, which varies as the fifth power of the stress, will also decrease (Holcomb and Hannum, 1982).

Besides affecting the time required for consolidation, the initial density may have another implication. A typical poured porosity is estimated at 35% to 40%, so that 35% to 40% of the total volume of the room with fill is gas or liquid. Whether these fluids will be extruded or vented during consolidation is not clear. If the fluids remain trapped in the pore spaces, they may prevent the fill from totally consolidating.

The permeability of crushed salt is of primary concern. To predict the effectiveness of crushed salt as a fluid barrier, the permeability associated with various stages of consolidation must be determined. Limited permeability measurements under various conditions have been reported with a wide range of results (Shor, Baes, and Canonico, 1981; Sullivan, 1983).

Moisture content and grain size distribution have been suggested as important variables in the consolidation of granular salt (Shor, Baes, and Canonico, 1981). However, constituents present in the WIPP brine, such as magnesium (Malecke, 1983) may significantly retard consolidation (Shor, Baes, and Canonico, 1981). Analysis of the as-mined salt will allow conducting future laboratory and field testing under conditions appropriate to the WIPP. Further, information on the as-mined condition will indicate the level of effort required to achieve conditions that may accelerate consolidation.

6.3.3.2. Activities

In 1984, various *laboratory engineering studies* were initiated. The grain size distribution of the as-mined salt was determined, and quasi-static compression and strength tests were performed (Pfeifle and Parrish, 1984).

Another series of *consolidation tests* was also begun. Some tests will be longer (30-day duration) to validate previous shorter duration tests. Other tests will evaluate the influence of moisture content and particle size. Permeability measurements at various times during these tests will measure the effectiveness of the salt at different stages of consolidation. In 1985, more laboratory testing under conditions suggested by the above investigations will be carried out to determine the mechanisms of consolidating granular salt.

Long-term compaction behavior will be estimated by numerical methods. Appropriate techniques and models will be developed for consolidating granular salt, as suggested by laboratory data. Initial calculations (Hunter, 1982; Kelsall et al, 1982) show a wide range of results, primarily from an unacceptably large variance in input values and from gross extrapolations of minimal existing data.

6.3.4. Tailored Backfills

6.3.4.1. Issues

Tailoring the backfills by adding materials other than granular salt may improve the properties of the backfill. Sodium bentonite, for example, could reduce the permeability of the fill while providing sorptive capabilities for radionuclides released from the waste. Tailored fill placed around waste could offer some benefits in a human intrusion (drilling) scenario. Laboratory investigations (Peterson and Kelkar, 1983) of various bentonite-based fills suggest that a 70/30 ratio of granular salt to granular bentonite may provide favorable properties in addition to being economical.

6.3.4.2. Activities

Evaluation of tailored fills will follow the same general scheme as for granular salt. Measurements will also be made of the sorptive properties under various conditions. Much preliminary work on bentonite-based fills has been done by the Waste Package Performance Program (Peterson and Kelkar, 1983).

6.3.5. Salt or Bentonite-Based Blocks

6.3.5.1. Issues

Using salt or bentonite-based blocks was suggested in Section 5.3. Salt blocks would allow for

emplacing relatively low-porosity salt in a drift, for reducing the time for reconsolidation, and for providing a more effective fluid barrier than salt backfill. Bentonite-based blocks will allow for constructing a low-permeability, radionuclide-retaining structure. They also should become more dense from the creep of the rock adjacent to the excavation, decreasing the permeability.

6.3.5.2. Activities

A *block testing program* will begin in 1984 to evaluate particle size, moisture content, applied pressure, and mix composition on block density, strength, and permeability. Deformational characteristics of blocks with optimal properties will eventually be investigated.

6.4. Geochemical Interactions

6.4.1. Introduction

Interactions between constituents of the plug, host-rock, and groundwater system may alter hydraulic and mechanical properties of the plug system, perhaps reducing or eliminating the plug's effectiveness. Materials engineered for penetration sealing are developed and evaluated on the basis of short-term laboratory tests. Material development strives for compatibility with the host environment, and *short-term* stability can be verified by appropriate testing. However, *long-term* interactions cannot be observed directly. Evaluation of materials emplaced long ago (Malinowski, 1981) and natural analog mineral occurrences (Roy, Grutzeck, and Wakeley, 1983) are secondary sources of longevity data, but are insufficient to confidently predict long-term behavior of these engineered barriers.

6.4.2. Cementitious Materials

6.4.2.1. Issues

Materials development has emphasized using cementitious grout because of available materials and technology. Cementitious plugs will usually not be in chemical equilibrium with their environment (Lambert, 1980a). Potential mineralogic phase changes in the plug, rock, and groundwater system could manifest themselves as (1) the formation of a soluble, friable, or permeable phase in the plug or nearby rock, or (2) shrinking or degradation of adhesion, resulting in opening the interface between the plug and the rock (Lambert, 1980a; 1980b). Examples of potential reactions with detrimental effects were given elsewhere (Lambert, 1980a; 1980b).

Petrographic examinations and property testing are periodically made at the WES of grout samples prepared when grouts for field studies were emplaced at the WIPP (Burkes and Rhoderick, 1983). To date, no unexpected results have been encountered. Inspection of a 17-yr-old grout recovered from a nearby potash mine also showed little evidence of exchange or reaction between the cement plug and the host rock (Buck and Burkes, 1979). These longevity studies are important and provide direct data. However, a method to predict long-term stability is required to give confidence in behavior that cannot be observed in one human lifetime.

6.4.2.2. Activities

Programs to address long-term geochemical stability of a cement plug have been proposed (Roy, Grutzeck, and Wakeley, 1983; Roy, Grutzeck, and Licastro, 1979; Lambert, 1980a; Lambert, 1980b). These programs outline extensive investigations, including chemical, thermodynamic, and kinetic considerations. The Plugging and Sealing Program will evaluate the applicability of these programs to the WIPP and will develop an appropriate program in 1985.

Sufficient plug and rock samples representative of all important environments at the WIPP are required for analysis. At the repository level, a *Plug Test Matrix* (Gulick, 1984) will be installed in 1984. This matrix will provide select candidate materials to be cured in situ in boreholes located in the WIPP horizon. Provisions will be made for installing plugs in wet and in thermally elevated, as well as ambient, environments. In addition, emplacements may be made from the shafts in key formations above the repository horizon (e.g., aquifers). Later recovery of these samples by overcoring will permit evaluating the effects of geochemical reactions.

Samples of the interface between the grout and/or concrete shaft liner and host rock can be cored periodically to permit evaluation of geochemical reactions in the Rustler Formation, particularly near the aquifers. Samples can be obtained of a grout-to-grout contact (the two pours in the BCT—Christensen and Peterson, 1981) cured in situ at 4460 ft (1360 m) in wellbore AEC-7 when the in situ testing of these grout plugs is complete.

6.4.3. Other Materials

Long-term geochemical stability of other materials used in sealing the WIPP will be evaluated when these materials are specified. Materials occurring naturally in the WIPP environment may be more geochemically compatible. The long-term stability of crushed salt is suggested by its composition, which is

identical to that of the host rock. Clays have existed for hundreds of millions of years in evaporites, evidencing considerable long-term stability (Roy, Grutzeck, and Wakeley, 1983). Preliminary investigations of bentonite indicate stability under conditions expected in a bedded salt repository (Roy, Grutzeck, and Wakeley, 1983; Krumhansl, 1984). Modifications to the program may be possible for evaluating cementitious plug stability to accommodate these other materials.

6.5. Mechanical Interactions

6.5.1. Issues

Designs of seals will need to consider all possible loads and mechanical interactions, between the seal components and the rock formation. These interactions include stresses and strains induced in the seal and the formation as a result of emplacing the seals.

As an example, consider a bulkhead (as described in Chapter 5) emplaced in a drift at the WIPP horizon. Deformation of the roof in contact with the bulkhead will be limited; deformation of the roof immediately adjacent to the bulkhead may not be constrained. As a result, the large differential strains may induce fractures that could provide for the flow of water to bypass the bulkhead. Another effect of a stiff bulkhead is the stresses induced in the formation surrounding the seal. Calculations indicate that these stresses could be great enough to heal fractures or to reduce the permeability of the formation (Kelsall et al, 1982). Shear stresses can be induced along the interface between the plug and the rock, perhaps increasing the hydraulic conductivity of the interface. Keys excavated for bulkhead construction could induce complicated and unfavorable stress distributions (Daemen et al, 1983). The effect of emplacing different materials adjacent to one another, as in multiple bulkheads, needs to be investigated.

Pressurizing a sealed room by gas generated from the waste or the formation could cause fractures in the formation or reduce the closure of the room. Initial calculations for the WIPP suggest that gas buildup will not cause detrimental effects (SNL, 1979). However, gas pressure of the formation was not considered, and the calculations did not reflect the waste volumes in the latest designs.

Fills will settle and consolidate with time and closure of the openings in salt, offering increased resistance to closure with time. Fills emplaced in the shafts may require some support, although this requirement may be reduced substantially by the tendency of the fill to transfer its weight to the host rock through "arching" (National Coal Board, 1982).

6.5.2. Activities

Numerical methods will be used to estimate possible mechanical effects from various seal designs. These methods will be most useful if they include time-dependent predictions for initiating, propagating, and healing fractures.

Previous gas pressurization studies will be evaluated in light of the latest data on gas production and dissipation at the WIPP. Further calculations will be made, if necessary.

6.6. In Situ Seal Performance

6.6.1. Issues

The performance of typical plugs emplaced at the WIPP must be measured before design verification. Size effects, emplacement techniques and equipment, and many operational considerations are significantly different in the field compared to the laboratory. Generally, seals will be of minimum length to expedite testing and to establish the minimum reference unit length for a particular seal (Section 4.4). The technique for emplacement must be achievable by the contractors who will eventually seal the WIPP.

The only in situ test of seal performance to date at the WIPP has been the BCT. A cementitious plug 8 in. (20 cm) in dia and 6 ft (2 m) long was installed and tested in 1979 at a depth of 4460 ft (1360 m) in the AEC-7 borehole near the WIPP site. Testing consisted of fluid buildup, shut-in, and tracer testing to determine the performance of the plug. This plug, subjected to the 1800-psi (12.4-MPa) pressure from the Bell Canyon aquifer, reduced the flow from 10,000 gal/day (38,000 L/day) to <16 gal/day (0.6 L/day) (Christensen and Peterson, 1981). A second plug was poured on top of the original plug in 1980, extending the total plug length to 18 ft. Testing of the extended plug was postponed because of equipment problems.

6.6.2. Activities

6.6.2.1. Borehole Plugs

AEC-7 is available for reentry and for testing the plugs in the *AEC-7 Reentry Test* (Stormont, 1984). The testing could occur in three phases, each consisting of a series of fluid buildup and shut-in tests, followed by removal by means of coring a portion of the plug. This sequence will provide for (1) duplicating of previous testing to infer changes after the plugs have remained in situ for almost 5 yr, (2) obtaining samples for geochemical evaluation of the grout,

(3) determining scaling effects, and (4) opening AEC-7 for hydrology testing. Another option is to emplace and test a plug in another portion of AEC-7 or another borehole, possibly in the Salado or Rustler Formations.

6.6.2.2. Backfills

Backfill emplacements in both waste and non-waste rooms at the WIPP will be evaluated as part of the Waste Package Performance (WPP) and PSP programs, respectively. These evaluations will use granular-salt and tailored backfills suggested by the materials development program.

The technique for backfill emplacement will be evaluated for as-placed backfill condition and operational considerations. Pneumatic stowing is a promising technique (Maksimovic and Draper, 1982; Maksimovic and Lipscomb, 1982). The initial density and extent (how near the roof, at the walls) of the as-placed fill will be examined. The sorptive capabilities of tailored fills containing clay will be evaluated. Actions such as wetting or compacting the fill that may assist in the consolidation process or improve the properties of the fills will be considered. Fills will be subjected to elevated and ambient temperatures, and to wet and dry conditions. Backfill emplacements in rooms J and T (Molecke, 1984) in 1984 and 1985 will investigate issues germane to waste-room emplacements. Backfill emplacements for nonwaste rooms will begin on a bench scale, culminating in 1987 in the backfilling of the heated room B (Munson, 1983).

Fills that may be placed in the shafts at the WIPP could be evaluated in a mockup in the repository or at a surface facility if it is not practical to test the fill in a shaft. Access to the fill from above in a shaft should aid in compaction efforts and in ensuring satisfactory contact of the host rock and fill along the entire circumference of the opening.

6.6.2.3. Small-Scale Seal Performance Tests

A series of tests determining the flow characteristics of seals in boreholes in the WIPP facility will precede large-scale bulkhead tests. These tests are called *Small-Scale Seal Performance Tests*. Scaling effects can be discerned by varying the diameter of the borehole (from ~4 in. to 36 in.). Vertical and horizontal emplacements can be evaluated. In the smaller diameter boreholes, using dyes and then overcoring the plug and a portion of the host rock may reveal flow

paths. In the larger diameter holes, the effects of interface and formation grouting and of keying may be determined. These activities are scheduled for 1985 and 1986.

6.6.2.4. In Situ Bulkhead Tests

Current conceptual designs call for locating modular bulkheads at key places in some drifts and perhaps in the shafts (Sections 5.2 and 5.3). These bulkheads may consist of several components. Concrete, salt blocks, and bentonite blocks are being considered. Several in situ tests on these components, or on individual components, are required to validate the performance and interactions of the bulkhead and the formation. Permeability testing of the gross formation before emplacing and testing bulkheads will provide baseline data on formation permeability.

The *In Situ Bulkhead Tests* (ISBTs) will be similar to the permeability test of the gross formation (Figure 12). Measurements will include temperature (thermocouples), stress changes (pressure cells), deformations of the formation and bulkhead (closure stations, extensometers), and flow characteristics (ultrasonics, guarded straddle packers, tracer sources and detectors). The tests will continue for some time to evaluate time-dependent effects. Interactions between the formation and the bulkhead (stress build-up, permeability changes, etc) will be investigated. Testing is expected to begin in 1986 or 1987.

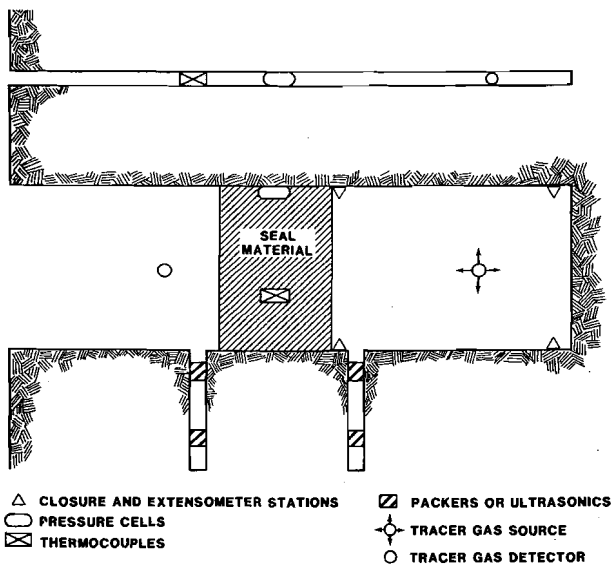


Figure 12. Example of In Situ Bulkhead Test Configuration

This testing will also provide much data for shaft bulkheads. If warranted, shaft bulkheads could be tested in a shaft, or in a repository or surface facility mockup.

6.7. Evaluation of the Seal System

6.7.1. Issues

The seal system must ensure that the radiological releases through existing penetrations at the WIPP do not jeopardize public health and safety. Thus, an important step in developing designs for sealing the WIPP is to determine the potential hazards associated with penetrations and the performance of the seal system that are needed to restrict the release to below the stipulated allowable limit. The seal system design will also incorporate the redundant barrier features required by EPA standards. Designs that will satisfy the required performance must then be identified and optimized based on the cumulative knowledge of the Plugging and Sealing Program's R&D activities.

To date, credible scenarios for breaching the WIPP have been identified (Bingham and Barr, 1978; Woolfolk, 1982) and consequence assessments of radionuclide release in these scenarios determined (US DOE, 1980; Woolfolk, 1982). In all analyses, many conservative assumptions were made about waste release rates, retardation of nuclides, postulated scenarios for breach events, and aquifer transmissivity and hydraulic gradients. In Appendix A and Chapter 3, these scenarios were used to estimate seal system performance to achieve the predicted low radiologic consequences to the public.

6.7.2. Activities

Further analysis will be made as more information is gained about factors affecting assessments of repository and seal system performance, and when required overall repository system performance is stipulated by the EPA. These analyses will allow development of sealing requirements and criteria that will be as applicable and realistic as possible for the WIPP site. Input of all the information gathered in the R&D on seal system performance will determine what designs will satisfy these requirements.

Parametric calculations of various sealing system designs will be used to optimize design variables such as location, thickness, and initial density of sealing components. The effects of sealing components both in series and in parallel with other components can be evaluated. Calculations of this nature may include determining the time required for saturating seal materials and the expected steady-state flow rates. Advancement of a wetting front to saturate a seal system may take thousands of years, depending on hydrologic and seal conditions (Gureghian, Scott, and Raines, 1983). Flow through a particular seal system must account for all four flow paths: the intact formation, the disturbed formation, the seal/rock interface, and the seal itself.

Preliminary calculations indicate the feasibility of such analyses. A model could be developed that allows for variation in as many design parameters as possible. Further testing, especially field testing, is required as input to place realistic bounds on certain parameters in this model.

7. Summary

The Plugging and Sealing Program will provide the technical basis for a defensible design for sealing the WIPP safely. Previous consequence assessments indicate that the technical requirements for WIPP seals may be minimal. The Plugging and Sealing Program will continue to develop and evaluate technology for limiting the release of radionuclides from the WIPP, striving to ensure that once they are stipulated, sealing performance requirements will be met. There is a high level of confidence that existing and developing technology will provide for adequate and acceptable sealing of the WIPP.

The overall Plugging and Sealing Program includes characterization of the formations and the repository, materials development, assessing geochemical and mechanical interactions, determining in situ seal performance, and seal system evaluation. Current conceptual designs call for using salt, cementitious materials, and clays as primary sealing materials. Issues and appropriate activities to address these issues will be continually evaluated and revised in light of further investigations. Close interfaces will be maintained with other experimental programs.

Activities to be conducted by the Plugging and Sealing Program and approximate beginning dates are summarized below. This list is not meant to be final. It allows for revision as the Plugging and Sealing Program evolves.

Activity	Beginning Dates
Characterization of the Formations and the Repository	
1. Measure in situ gas permeability in boreholes	FY84
2. Make permeability measurements of the gross or bulk formation	FY86
3. Develop ultrasonic measurement	FY84
4. Test laboratory permeability, as required	FY84
5. Monitor fractures	FY84

Materials Development

- | | |
|---|------|
| 1. Refine baseline grout mixtures | FY84 |
| 2. Develop appropriate concretes | FY84 |
| 3. Develop block manufacture technique | FY84 |
| 4. Investigate salt and bentonite backfill and block mechanical and hydrologic properties | FY85 |

Geochemical Interactions

- | | |
|---|------|
| 1. Install plug test matrix | FY84 |
| 2. Evaluate sample from shaft liner | FY85 |
| 3. Evaluate sample from AEC-7 | FY86 |
| 4. Develop and apply geochemical analysis program | FY85 |

Mechanical Interactions

- | | |
|--|------|
| 1. Develop mechanical interactions program | FY85 |
| 2. Obtain predictions for bulkhead/formation interactions to support in situ testing | FY86 |

In Situ Seal Performance

- | | |
|---|------|
| 1. Reenter AEC-7 to test plugs, or emplace and test another borehole plug | FY86 |
| 2. Test in situ small-scale seal plug performance | FY85 |
| 3. Test in situ bulkhead | FY86 |
| 4. Evaluate backfill emplacements
RM J and T* | FY85 |
| RM B** | FY87 |

Seal System Evaluation

- | | |
|---|------|
| 1. Model and assess the design of the seal system | FY87 |
| 2. Develop preliminary design criteria | FY88 |

*Responsibility of WIPP Program

**Responsibility of TSI Program

Figures 13, 14, and 15 are tentative schedules of reports, programs, and lab and field tests for fiscal years 1984, 1985, and 1986, respectively. These schedules are subject to change, particularly the field tests because of site constraints. Figure 16 is an overview of major milestones.

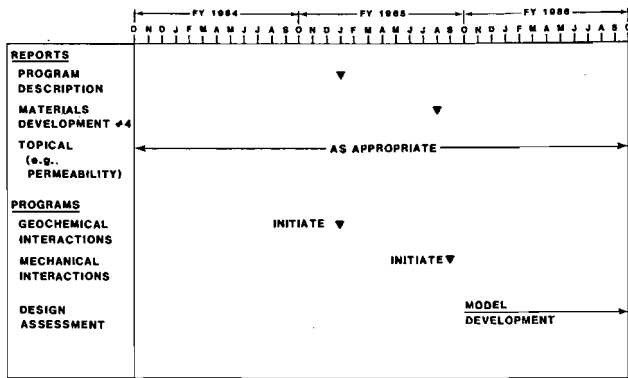


Figure 13. Schedule for Reports and Programs in FY84, FY85, and FY86

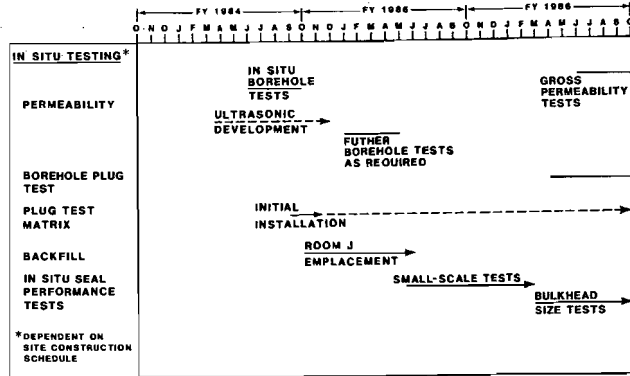


Figure 15. Schedule of In Situ Testing in FY84, FY85, and FY86

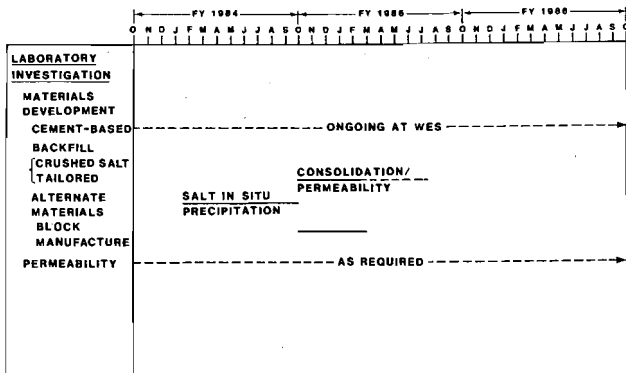


Figure 14. Schedule of Laboratory Investigations in FY84, FY85, and FY86

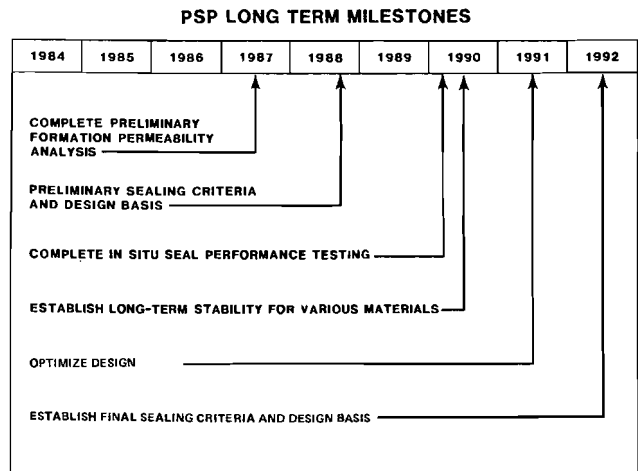


Figure 16. Tentative Long-Term Milestones for the Plugging and Sealing Program

Appendix A

Estimating Sealing Requirements

A.1 Introduction

The FEIS (US DOE, 1980) and the SAR (US DOE, WIPP, 1980) both contain consequence assessments. These assessments calculate the flow through the repository and the subsequent migration of radionuclides to the biosphere resulting from man-made penetrations.

Two fundamental modes in which one or more penetrations could establish hydraulic communication between an aquifer and the repository (US DOE, 1980; US DOE, WIPP, 1980), Figure A1, are (1) single-aquifer (Rustler) communication, and (2) two-aquifer (Rustler and Bell Canyon aquifers) communication. The driving force for flow in the single-aquifer communication can be either diffusion for a single, isolated penetration or the hydraulic potential developed between two or more penetrations (connected by means of the repository) as a result of the hydraulic gradient of the Rustler (the so-called U-tube connection). The driving force for the flow in the two-aquifer communication is the difference in hydraulic potential between aquifers. Two-aquifer communication can cause a much greater flow rate, which in turn results in a greater dose to the maximally exposed person (US DOE, 1980; US DOE, WIPP, 1980).

These scenarios are assumed to begin 1000 yr after waste emplacement. However, earlier breaching does not result in significantly different radiologic consequences. The reason is that the minimal time of hydrologic transport in the Rustler discharge in the Pecos River (conservatively estimated at ~5000 yr) is long enough for the highly active, short-lived fission products to decay, leaving only the long-lived actinides (US DOE, WIPP, 1980).

Two approaches were taken to relate these scenarios to sealing requirements. Scenarios involving open penetrations were examined to reveal the consequence of no seal. This approach was used for estimating the requirement to seal boreholes. Other scenarios involved minimally sealed penetrations that offer some resistance to flow. From these scenarios can be estimated the seal material and design to produce a similar hydrologic resistance, and hence, radiologic dose.

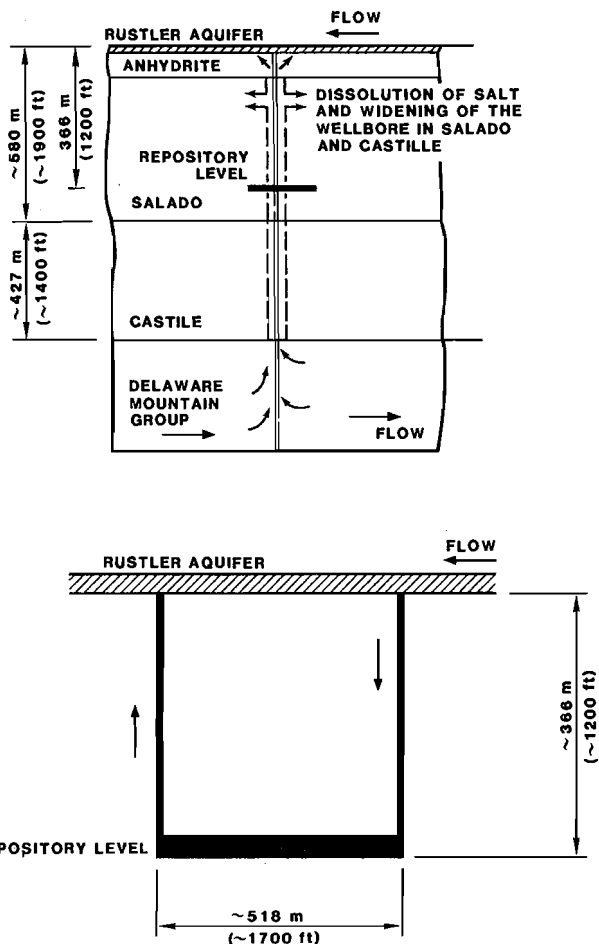


Figure A1. Two Possible Modes of Hydraulic Communication Involving the WIPP Repository (from US DOE, 1980)

Pressurized brine intrusion scenarios (Woolfolk, 1982) were also examined to estimate seal requirements. These scenarios assume isolation of portions of the waste from one another. The implied requirements of seals are to structurally resist the pressurized brine, and not to allow involvement of waste-contaminated brine from other storage areas in the release event.

The intent of these calculations is not to determine requirements for sealing the penetrations associated with the WIPP, but rather to indicate the magnitude of sealing that may be required. It is helpful while conducting R&D to have some idea of the extent of the problem to be solved, a reference that will aid in preliminary evaluations of seal designs. It is recognized that these calculations are simplistic (but conservative), and more complex calculations may be appropriate in the future.

A.2 Boreholes

As part of the FEIS (US DOE, 1980), the consequences of a two-aquifer communication scenario were evaluated. In this scenario, an uncased, *open* borehole penetrates through the Rustler, the center of the repository, and the Bell Canyon aquifer. A total of 600 ft³/day (17 m³/day) of unsaturated brine (230,000 ppm) is allowed to enter the borehole from the Bell Canyon aquifer. The brine dissolves the salt along the borehole and the salt and waste in the repository, and enters the overlying Rustler aquifer as a saturated brine (410,000 ppm).*

Under the conservative conditions evaluated in the FEIS, all wastes from the storage horizon—6,330,000 ft³ (180,000 m³) of contact-handled waste and 250,000 ft³ (7100 m³) of remote-handled waste—are removed in ~1.3 my. The whole-body dose received by the maximally exposed individual from this scenario is 0.008 mrem/yr. The natural background radiation on the surface near the WIPP site is ~67 mrem/yr (Minnema and Brewer, 1983). Thus the radiologic dose from this scenario is ~0.012% of the natural background radiation near the WIPP site.

A later study (Intera Environmental Consultants, 1983) incorporated more recent and representative hydrologic data into calculations to predict maximum flow rates for various scenarios. The maximum flow rate in the two-aquifer communication scenario was given as 100 ft³/day (3 m³/day), rendering the FEIS consequence based on 600 ft³/day (17 m³/day) even more conservative. Further, this maximum flow rate

was calculated based on 25 open boreholes (located within a 1-sq-mi grid symmetric about the site center) that connected the Rustler Formation, the repository, and the Bell Canyon Formation rather than one borehole as in the FEIS. Thus, even for multiple open boreholes and two-aquifer communication with the boreholes passing through the repository, the flow established is less by a factor of 6 than that which would result in a maximum dose of ~0.01% of the natural background radiation.

Travel times for the Rustler to discharge in the Pecos River are currently estimated as an order of magnitude greater than those used in the FEIS and the SAR (Barr, Miller, and Gonzales, 1983). These times will therefore allow for more actinide decay before possible human exposure than was previously accounted for. Recent measurements also suggest that the direction of flow may be downward rather than upward, and calculated consequences would be reduced. The reason is that travel times in the Bell Canyon Formation are 10 to 100 times greater than in the Rustler (Mercer, 1983). Thus, the maximal dose reported in the FEIS can currently be considered a very conservative upper bound.

No boreholes exist that pass through both the upper and lower aquifers and the repository. Considering the various boreholes that do exist shows that (1) the consequences of the previously evaluated scenarios are indeed a very pessimistic worst case, and (2) sealing the boreholes at the WIPP may not be required from the viewpoint of public health and safety.

Existing boreholes at the WIPP can be categorized as (1) penetrating both the Rustler and Bell Canyon aquifers (but *outside* the bounds of repository), or (2) penetrating the Rustler and terminating in the Salado. All such boreholes are inconsequential unless and until they introduce water to the repository. To do so, the flows established in the boreholes must provide for dissolving the salt that separates the borehole and the repository.

The maximum flow rate established in the first type of borehole (two-aquifer communication) was conservatively calculated as 30 ft³/day (1 m³/day) for a single borehole (Intera Environmental Consultants, 1981). Assuming that fresh water will dissolve 20% of its volume in solids before it becomes saturated, this flow rate corresponds to enlarging the borehole by 6 ft³/day. At this rate, it will take ~4 my for a borehole to enlarge to 1000 ft (305 m). (The closest that a borehole of this type exists at the WIPP is 1000 ft horizontally from the repository boundary.) Subsequent dissolution and transport of the waste will necessarily result in less consequence than that of the

*All dissolution calculations in this report assume radially uniform dissolution along the penetration. This is most likely *not* the case. The central portion of the salt will probably experience less dissolution than will the salt near the water source. Further, no attempt was made to determine the closure of the penetration from creep. It may be that the penetrations close faster from creep than they enlarge from dissolution.

worst-case scenario previously presented (flows occurring through the repository within 1000 yr after emplacing the waste). The reason is that the actinides will have further decayed in the time required for borehole enlargement.

The boreholes that intersect the aquifers only above the repository (single aquifer) do not have a significant mechanism for circulating water for continuing dissolution. In a 2000-ft(610-m)-deep fully open 6-in.-(15-cm)-dia wellbore, diffusion in the water column in the borehole results in a flux velocity of $\sim 10^{-6}$ ft/day (3×10^{-7} m/day) (US DOE, 1980). At this rate, $\sim 10^{-5}$ ft³/yr (3×10^{-8} m³/yr) of salt can be dissolved. If a borehole of this type did intercept the repository, the mechanism for transporting radionuclides to the Rustler would still be diffusion at a very slow rate. Further, even if a U-tube connection was eventually established, the consequences would be negligible when compared to consequences of the two-aquifer scenario (US DOE, 1980; US DOE, WIPP, 1980).

Placing seals or plugs in boreholes will reduce the flow and hence the potential for any release of radionuclides to the biosphere. Although low flow rates will result from competent cement plugs, the question remains of plug degradation and performance with time. If it is assumed that a sanded-grout plug will eventually degrade into its constituents, the condition of the plug would be comparable to that of sand. Calculations for a borehole 8 in. (20 cm) in diameter and 2400 ft (732 m) long, backfilled with 10-D sand, predict a flow rate of 0.4 ft³/day (0.01 m³/day) for the previously described two-aquifer scenario (Intera Environmental Consultants, 1981). (This scenario was the two-aquifer communication through the center of the repository.) With this flow rate, it would take more than 30 my, compared to 1.3 my for the unplugged case, to dissolve the repository contents. Thus, it is clear that even if cement degrades to a condition equivalent to that of sand, substantial resistance to flow will naturally persist.

Based on previous calculations, boreholes pose no apparent threat to public health and safety. However, prudent regard for public health and safety (as emphasized in Section 3.1) and (undoubtedly) future regulations, will dictate some sealing. Appendix B presents proposed criteria for determining which boreholes in the vicinity of the WIPP will require sealing beyond common oil-field practices.

A.3 Shafts

A fundamental difference between shafts and boreholes at the WIPP is that shafts provide for direct communication between aquifers above the repository and the repository itself. Thus, while water in existing boreholes must dissolve salt or proceed along some other anomalous, unlikely path to reach the repository, water in the shafts need not. Because the shafts do not extend much deeper than the repository horizon two-aquifer communication scenarios do not apply. However, U-tube communication (single-aquifer) established through the shafts is plausible.

The U-tube scenarios evaluated in the FEIS and the SAR resulted in a whole-body dose to the maximally exposed individual of 0.01% of the natural background radiation. In this scenario, both the repository and the upstream and the downstream wellbores resisted flow, limiting the flow rate to ~ 2 ft³/day (0.06 m³/day) (US DOE, WIPP, 1980). A worst or reasonably limiting case of *no* resistance to flow for 25 hypothetical penetrations contained within 1 mi², symmetric about the site center and establishing a U-tube connection through the repository, results in a flow rate of 26 ft³/day (0.07 m³/day) (Intera Environmental Consultants, 1981). The consequences of this maximum flow rate cannot be directly related to the doses reported in the FEIS and the SAR. However, it would seem reasonable that because of the very conservative nature of the calculations and the long travel times required to reach the biosphere, a flow rate on the order of 10 times greater than that resulting in a maximum dose of $\sim 0.01\%$ of the natural background radiation would not result in a consequential dose to the maximally exposed individual.

An alternate way to assess a U-tube scenario involving shafts is to determine the type and the amount of sealing materials in the shafts that will result in a flow rate of 2 ft³/day (0.06 m³/day). The same flow rate as predicted in the FEIS and the SAR will be achieved if the hydraulic conductance of the penetration remains constant. The hydraulic conductance, the inverse of the resistance, is defined as

$$HC = \frac{KA}{L}$$

where K is the permeability, A is the cross-sectional area, and L is the length of the seal. The scenarios evaluated for the FEIS and the SAR specified a 2-ft(0.6-m)-dia wellbore with an effective permeability of 20 D over a 1200-ft (366-m) length, yielding

$$HC = \frac{(20D)(3.1 \text{ ft}^2)}{(1200 \text{ ft})} = 0.052 \text{ D-ft}$$

Figure A2 presents the length vs effective permeability of seal material to have a hydraulic conductance equivalent to 0.052 D-ft in three 20-ft-dia shafts and, hence, a flow not exceeding 2 ft³/day (0.06 m³/day). Table A1 presents measured permeabilities of candidate seal materials. The values given for the BCT 1-FF grout in anhydrite are effective permeabilities because the measurement encompassed the rock/seal system. In comparing Figure A2 with Table A1 we see that short lengths of seals would be required to produce a flow rate of 2 ft³/day and the resulting low radiologic dose. Note that the required permeabilities are *effective* permeabilities; that is, all interface and disturbed zone as well as seal contributions to the overall permeability are implicitly contained in the effective permeability.

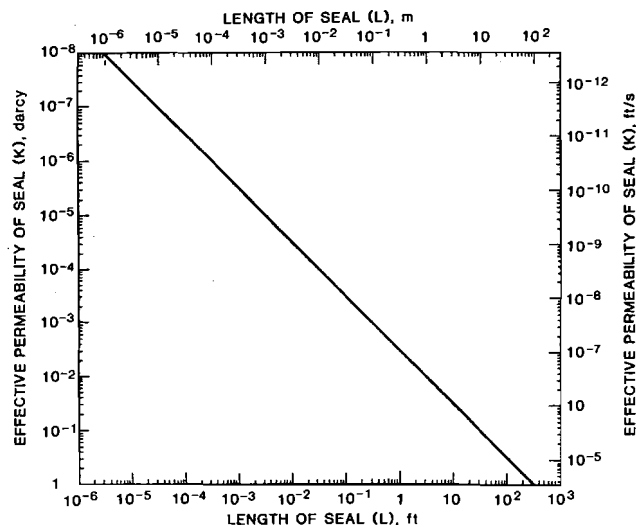


Figure A2. Length of Seal vs Permeability of Seal Required for a Flow of 2 ft³/day (0.6 m³/day) in Three 20-ft-Dia Shafts

Table A1. Measured Permeabilities of Candidate Sealing Materials

Material	References (see reference for test conditions)	Permeability (D 10 ⁻⁶)
Rock salt (in situ)	Peterson et al, 1981	10 to 20
Rock salt (laboratory, healed)	Sutherland and Cave, 1979	0.05
Rock salt (laboratory, <i>not</i> healed*)	Cooley and Butters, 1979	1 to 100
BCT 1-FF in anhydrite	Christensen and Peterson, 1981	50
BCT 1-FF in anhydrite (laboratory)	Gulick, Boa, and Buck, 1980	0.5 to 10
BCT 1-FF (laboratory)	Gulick, Boa, and Buck, 1980	1 × 10 ⁻¹
Crushed salt** (laboratory, consolidated, healed*)	Sullivan, 1983	1 × 10 ² to 1 × 10 ³
Crushed salt** (laboratory, consolidated, <i>not</i> healed)	Sullivan, 1983	1 × 10 ³
70% crushed salt, 30% bentonite** (laboratory, consolidated)	Peterson and Kelkar, 1983	5.3 × 10 ²
Bentonite** (laboratory, consolidated)	Peterson and Kelkar, 1983	0.34

*Healing refers to leaving the sample hydrostatically stressed for some time (typically, at least 48 hr) before making measurement.

**Backfill material permeability depends on how the material was emplaced and the time after emplacement being considered. "Consolidated" backfill may be the initial condition of a compacted backfill or a backfill that is at some stage of densification as a result of pressure from the creep closure of rock surrounding the excavation.

A4. Horizontal Penetrations

Minimal resistance to flow in the repository was used in calculating the U-tube scenario in the SAR and the FEIS. Thus, to be consistent in using these scenarios to develop requirements for sealing shafts, the repository horizon should offer at least an equivalent resistance to that used in these scenarios. The SAR scenario (US DOE, WIPP, 1980) specified an effective permeability of 10 D and a flow length of 3100 ft (1030 m), a width of 1430 ft (440 m), and a height of 12 ft (4 m), yielding

$$HC = \frac{KA}{L} = \frac{(10D)(12 \text{ ft} \times 1430 \text{ ft})}{(3100 \text{ ft})} = 55 \text{ D-ft}$$

Figure A3 presents the length vs effective permeability of seal material in the repository for a hydraulic conductance of 55 D-ft, and hence, a flow not exceeding 2 ft³/day (0.06 m³/day). As with shaft seals, short lengths of candidate seal materials are required to produce this flow and associated low radiologic dose (see Table A1).

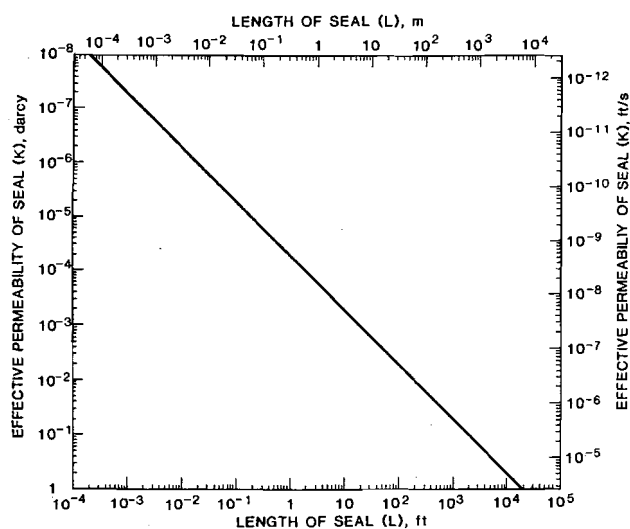


Figure A3 Length of Seal vs Permeability of Seal Required for a Flow of 2 ft³/day (0.06 m³/day) Through the Repository

A further consideration in determining the need to seal the underground workings is the desire to separate and isolate portions of waste from one another. This will minimize hazards such as human intrusion in the form of drilling by not exposing the entire waste inventory to the breaching mechanism. The design of the WIPP storage area provides for panels that can be isolated from one another by placing seals or bulkheads at the entries to each panel. Such seals are implicitly involved in pressurized brine intrusion scenarios.

An assumption made in evaluating the consequences of these scenarios is that only a limited volume of waste is available to the release mechanism (the borehole connecting the repository containing pressurized brine and the surface). This infers that seals can provide enough isolation. The radiologic consequence of these scenarios did not exceed draft statutory release limits (Woolfolk, 1982); it is not obvious what the expected release would be if the seals did not isolate portions of the waste inventory. Further, the influence of a tailored fill instead of a crushed-salt fill over the waste was not examined.

The worse-case pressurized brine scenario involved one drillhole that would allow brine to saturate the affected storage area, and another hole drilled at some later date to release the waste-contaminated brine to the surface for 24 hr before the flow stopped. The function of the seal, then, is to restrict release to the storage area containing the boreholes for 24 hr. It is unreasonable to expect the seal *not* to allow any flow away from the affected storage area during the period between brine flow and release to the surface. Any material with a finite permeability will allow some brine to flow from high to low pressures. Instead, the seal must not allow involvement of any waste-contaminated brine from these outside areas in the release event. One way to assure this is for travel times in the seal to exceed the 24-hr release period.

Travel time through a seal, assuming one-dimensional steady-state flow, is given by

$$t = \frac{\phi L^2}{K \Delta h}$$

where

- K = effective seal permeability
- Δh = the pressure head difference across seal
- ϕ = the porosity of the seal
- L = the seal length.

Assume a 24-hr release period and a connected porosity of 0.01. The maximum pressure across the seal would be 1535 psi (10.6 MPa) because the maximum static pressure is 2665 psi (18.4 MPa) and is reduced to 1130 psi (7.8 MPa) shortly after flow in the affected storage room to the surface begins (Woolfolk, 1982). The pressure head would then be 2905 ft. Figure A4 shows the resulting relationship between the seal length and the effective permeability required to produce a 24-hr travel time in the seal.

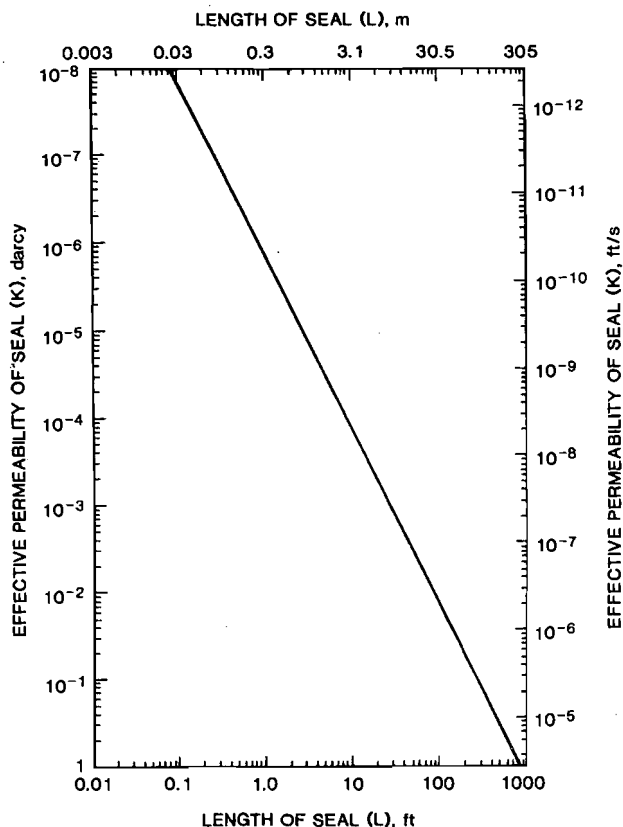


Figure A4. Length of Seal vs Permeability of Seal Required for a Travel Time >24 hrs in a Seal at WIPP Horizons

For the seal to isolate storage areas during the release event, it must be able to structurally resist the pressurized brine. The seal resists this pressure (2665 psi maximum) by developing frictional resistance along the interface. The maximum shear strength of any point along the interface is given by

$$\tau = c + \sigma_n \tan\phi$$

where

c = cohesion

σ_n = normal stress across interface

ϕ = friction angle

τ = shear strength.

The total strength of the interface is determined by summing the strength at every point over the entire interface (Stormont and Daemen, 1983). This is done by integrating over the surface of the plug; i.e.,

$$S = \int_0^L \int_0^{2\pi} \tau r d\theta dx$$

where

r = seal radius

L = seal length

S = total strength.

Substituting yields

$$S = \int_0^L \int_0^{2\pi} (c + \sigma_n \tan\phi) r d\theta dx$$

Neglecting (1) roughness or bonding along the interface, (2) expansive stress of the seal material, (3) dilatancy-induced stresses, or (4) the Poisson effect during loading yields

$$S = (\sigma_r \tan\phi)(r)(2\pi)(L)$$

where

σ_r = normal stress across the interface due to the stress buildup from creep of the rock surrounding the plugged excavation.

The radial stress buildup has been estimated as approaching 75% of lithostatic (~1500 psi) in ~100 yr (Kelsall et al, 1982). The friction angle for a cement-rock interface has been estimated as 30° to 40° (Clairborne and Gera, 1974). Let the radius equal 10 ft (3 m). Failure occurs when the applied load equals the strength, i.e.,

$$S = 2665 (\pi)(10^2) = 1500(\tan 30^\circ)(10)(2\pi)L .$$

Solving for L gives

$$L = 15.4 \text{ ft (4.7 m) .}$$

This very conservative calculation estimates that a concrete bulkhead ~15 ft long should resist structurally the anticipated maximum pressures from a brine reservoir inflow into the repository.

From the viewpoint of both structure and leakage (travel time), seals that should be achievable satisfy the implied performance of the pressurized brine intrusion scenarios.

Appendix B

Proposed Criteria for Identifying Penetrations That Require Sealing in Compliance With Performance Requirements

Penetrations in the vicinity of the WIPP are categorized as to how far they are from the site center (Figure B1) and the depth to which they penetrate (Figure B2). Every penetration will fall into one of three conditions:

- **Condition 1.** Penetration terminates in the Salado and in or within 1000 ft (305 m) horizontally of the maximum potential lateral extent of repository development. Note that all three shafts (and the horizontal penetrations) are in this condition.
- **Condition 2.** Penetration terminates below the Salado/Castile interface within 2 mi of the site center.
- **Condition 3.** Penetrations drilled by DOE within 3 mi of the site center and not included in Conditions 1 or 2.

Table B1 summarizes penetrations to be plugged.

Criteria have previously been proposed (Christensen, Lambert, and Gulick, 1982) for identifying which penetrations should be sealed in excess of existing statutory requirements. These criteria divide existing penetrations that are the responsibility of the DOE into two categories: (1) those to be sealed as dictated by the performance requirements (yet to be determined), and (2) those that can be sealed in compliance with State of New Mexico legislation. These criteria, based on very conservative calculations, are reasonable in light of the calculations and discussions on sealing requirements in Appendix A. These criteria are tentative and subject to refinement.

Two sets of criteria are proposed for plugging penetrations (Christensen, Lambert, and Gulick, 1982):

- **WIPP Plugging Criteria (WPC).** These criteria are suggested for wellbores meeting Condition 1 or 2. They would require methods for plugging

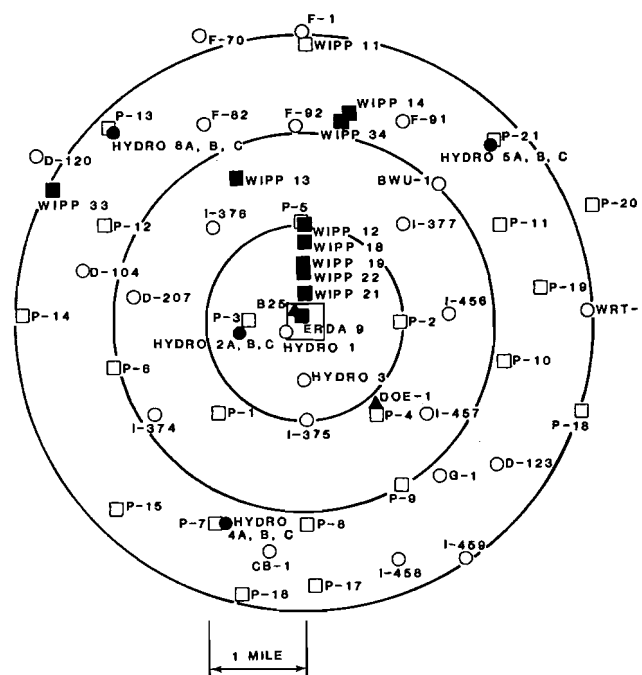


Figure B1. WIPP Site Drillhole Locations

wellbores relating to facility integrity and public safety, and thus more stringent than existing statutory legislation. Penetration zones within the Rustler, Salado, and Castile Formations would be plugged as suggested by the sealing concepts of Chapter 5 that will meet performance requirements.

- **State of New Mexico (SNM) Criteria.** These criteria are mandated by statutory legislation. They will be applied to penetrations *not* meeting Condition 1 or 2, for which the DOE is responsible. The SNM criteria are contained in State of New Mexico Rules and Regulations; Order No. R-111-A; State of New Mexico Statutes Annotated.

- CONDITION 1: TERMINATION IN SALADO WITHIN 305 m(1000 ft) OF MAXIMUM POTENTIAL LATERAL EXTENT OF REPOSITORY DEVELOPMENT** **WPC**
- CONDITION 2: TERMINATION BELOW SALADO/CASTILE INTERFACE WITHIN 2 MI OF SITE CENTER** **WPC**
- CONDITION 3: ALL OTHER PENETRATIONS WITHIN 3 MI OF SITE CENTER** **SNM**

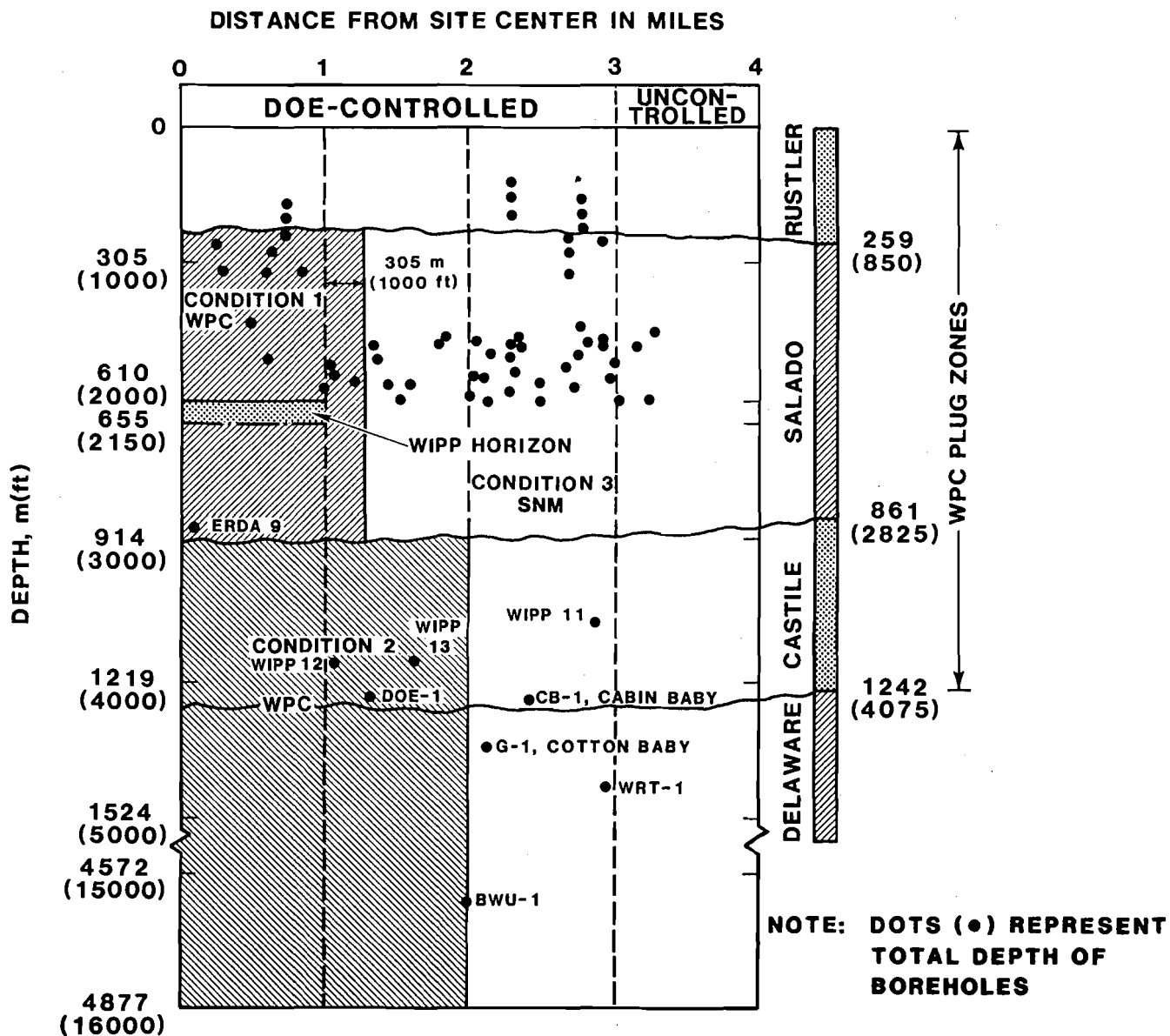


Figure B2. Classification of Drillholes at the WIPP Site as to Location (Depth and Distance from Site Center) (From Christensen, Lambert, and Gulick, 1982)

Table B1. Summary Penetrations to be Plugged Within WIPP Zone 1, 2, 3, and 4 Boundaries*

Zone	Total Penetrations	Criteria		Plugged and Abandoned
		WPC	SNM	
1	2	2; rework 2 to WPC		
1	3 shafts	3 (shafts)		0
2	11	9; rework 2 to WPC		2
3	16	7; rework 6 to WPC		1
4	40	0	0	19
Totals	69	18; rework 10 to WPC		22
Plus	3 shafts	3 shafts		0

For sealing criteria purposes:

- 18 wellbores plus 3 shafts required WPC plugging criteria.
(10 of these wellbores require rework to satisfy WPC.)
- 22 wellbores need plugging in accordance with SNM criteria.
29 wellbores were plugged and abandoned.

*A limited number of shallow foundation holes (<200 ft deep) have been drilled under separate contract for the US DOE (designated "B" holes) and are not included in this tally. These do not qualify under WPC since penetration of the Rustler Formation did not occur. These will be plugged under SNM criteria.

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