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Preliminary Seal Design Evaluation for the Waste Isolation Pilot Plant

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PRELIMINARY SEAL DESIGN EVALUATION FOR THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

This report presents a preliminary evaluation of design concepts for the eventual sealing of the shafts, drifts, and boreholes at the Waste Isolation Pilot Plant Facility. The purpose of the seal systems is to limit the flow of water into, through, and out of the repository. The principal design strategy involves the consolidation of crushed or granular salt in response to the closure of the excavations in salt. Other candidate seal materials are bentonite, cementitious mixtures, and possibly asphalt. Results from in situ experiments and modeling studies, as well as laboratory materials testing and related industrial experience, are used to develop seal designs for shafts, waste storage panel entryways, non-waste containing drifts, and boreholes. Key elements of the ongoing experimental program are identified.

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PRELIMINARY SEAL DESIGN EVALUATION FOR THE WASTE ISOLATION PILOT PLANT

1. PURPOSE OF THE REPORT

This report is a preliminary evaluation of design concepts for the sealing of penetrations (shafts, drifts, and boreholes) at the Waste Isolation Pilot Plant (WIPP) Facility. This evaluation is a product of the Plugging and Sealing Program (PSP), an experimental program conducted by Sandia National Laboratories (SNL) for the Department of Energy (DOE). The goal of the PSP is to develop the design concepts, bases, and criteria for the effective, long-term sealing of the WIPP Facility. A final conceptual design evaluation providing all input and information from the PSP is required to support the 1993 DOE decision whether to convert from pilot plant status to an operating repository.

This preliminary evaluation will

- Allow the application of results and experience to update the design concepts for the WIPP
- Provide direction for the ongoing experimental program
- Provide input for the decision for the first receipt of waste, presently scheduled for October 1988.

This preliminary evaluation draws information and data principally from the PSP, although other sources have been utilized when appropriate. These other sources include other facets of the DOE's program investigating the suitability of the WIPP as a nuclear waste repository, other experimental programs for sealing nuclear waste repositories in salt and other geologic media, and mining-related research and experience. Although substantial information is available to support this evaluation, many data and models are not presently available or adequately understood. Thus, estimates, extrapolations from limited data, inferences, and judgements have been used in this evaluation.

2. SITE STRATIGRAPHY

Sealing activities for the WIPP will be largely directed at the Rustler and Salado Formations (the generalized WIPP site stratigraphy is given in Figure 2.1). Some existing boreholes in the vicinity of the WIPP site will penetrate the formations underlying the Salado, and will therefore require sealing the Castile Formation. The Dewey Lake Red Beds above the Rustler and the Delaware Mountain Group below the Castile are zones in which a seal adds little to restricting transport because the zones themselves are relatively permeable compared to salt (Christensen, Gulick, and Lambert, 1981).

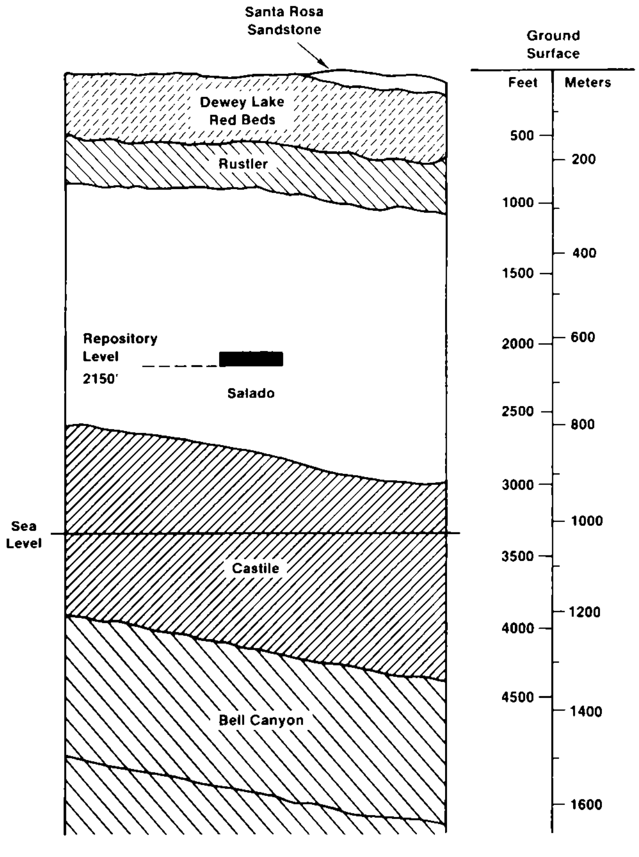

Figure 2.1. Generalized WIPP Site Stratigraphy.

Mapping the shaft walls prior to liner installation provided a good record of the lithology of the Rustler Formation from 168 to 257 m below the surface. The Rustler lithology is very diverse, being composed of carbonates, sulfates (gypsum, anhydrite, and polyhalite), clastic rocks, and halite (US DOE, 1983; US DOE, 1984). The Rustler contains the 8 m thick, water-bearing Magenta and Culebra dolomite beds at 186 and 220 m below the surface, respectively. The Culebra is considered the most transmissive unit in the Rustler, with transmissivities in the range of 2 x 10^{-5} to 1 x 10^{-3} m^2/s (Mercer, 1983). The transmissivities of the Magenta vary from 4 x 10^{-7} to 6 x 10^{-4} m^2/s (Mercer, 1983). In addition, the Rustler/Salado contact is transmissive in some locations in the vicinity of the WIPP site (Haug et al., 1986), but has not produced water in the WIPP shafts (US DOE, 1983; US DOE, 1984). Mechanical properties of the Rustler rocks have not been determined, but can be estimated from generic properties such as those compiled by Lama and Vuturkuri (1978) and Callahan (1981).

The Salado Formation, from the base of the Rustler to 850 m below the surface, is primarily halite, but also includes thin beds of anhydrite, polyhalite, clay zones, and in some areas, potash minerals. Numerous excavations and boreholes have provided a detailed and extensive characterization of the WIPP Facility horizon stratigraphy (e.g., US DOE, 1986). Krieg (1984) presents a reference stratigraphy and rock properties for the facility horizon, including the reference constitutive model for time-dependent salt deformation (creep). Permeabilities of the Salado rocks calculated from tests made from surface wellbores are generally in the range of 10^{-18} m^2 or lower

(Mercer, 1986; Peterson et al., 1979). Numerous gas permeability measurements have been made from the facility horizon. At locations well removed from the excavations, the inferred permeabilities are very low ($<10^{-20}$ m^2); close to the excavation the permeability can increase 3 orders of magnitude or more (Stormont, Peterson, and Lagus, 1987). Brine testing from the facility horizon indicates permeabilities consistent with the gas test values, but also a substantial pore or formation pressure (Peterson, Lagus, and Lie, 1987a).

The Castile extends from the bottom of the Salado to 1220 m below the surface. It consists principally of thick anhydrite beds with some interbedded halite. Pressurized brine has been encountered several times in the uppermost Castile anhydrite, and is believed to be contained within localized, isolated reservoirs that are chemically and hydraulically in equilibrium with their environment (Popielak et al., 1983).

3. FACILITY DESIGN

The WIPP waste emplacement rooms are being developed approximately 650 m below the surface in the Salado Formation, about 400 m below the Rustler/Salado contact, and 200 m above the Salado/Castile contact. The three shafts which currently afford access to the repository are:

- o The Construction and Salt-Handling Shaft (C&SH), 3.7 m drilled diameter
- o The Waste Shaft, 6.1 m slashed diameter
- o The Exhaust Shaft, 4.6 m slashed diameter.

All three shafts are lined through the overlying Dewey Lake Red Beds and the Rustler Formation, and have a liner key or foundation located nominally 18 m into the Salado. The liners in the waste and exhaust shafts are concrete, while the C&SH shaft incorporates a steel liner cemented in place. Details regarding the design, construction, and maintenance of the shafts are given in the Final Design Evaluation Report (US DOE, 1986). A fourth shaft, nominally 6.0 m diameter, is presently being constructed by up-reaming.

Excavation at the facility horizon began in 1982. With the exception of the C&SH shaft station, which was excavated by drilling and blasting, excavations have been created by mining machines (continuous miners). A plan view of the underground development is given in Figure 3.1, and can be divided into the experimental area to the north of the shaft stations and the waste storage panels to the south. Within the experimental area, the drifts are at two levels: to the west drifts have been developed at the disposal horizon; to the east drifts have been developed so their floor is about 2 m above the roof of the disposal horizon. The stratigraphy associated with the two levels is given in Figure 3.2. Information on the underground construction, completed and planned, is given by the US DOE (1986).

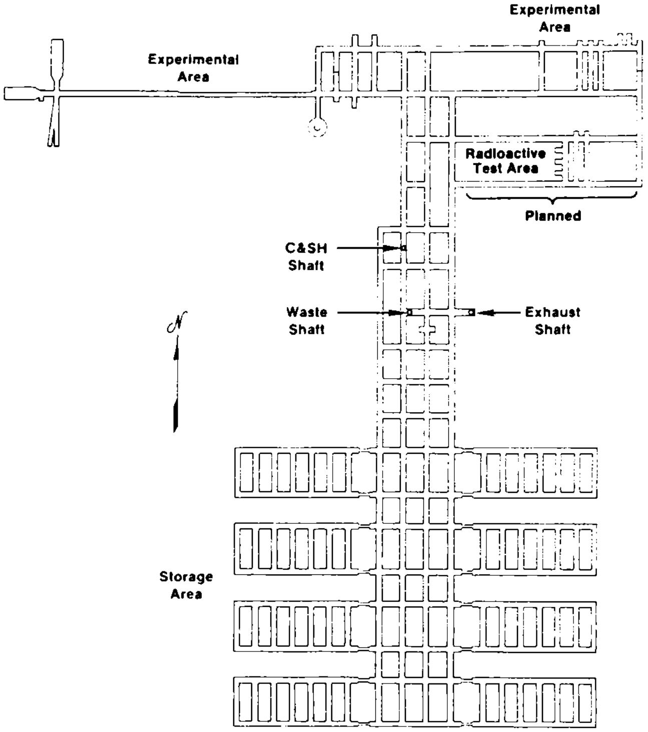

Figure 3.1. Plan View of the Proposed WIPP Facility.

Waste to be stored/disposed at the WIPP will be contact handled transuranic (TRU) wastes in 55-gal drums and remote handled TRU waste in canisters. It is presently planned that the contact handled waste will be packaged and handled in groups of seven drums which will be stacked three high within the storage rooms. The remote handled waste will be emplaced in 91 cm diameter horizontal boreholes in the ribs of some of the contact handled TRU storage rooms.

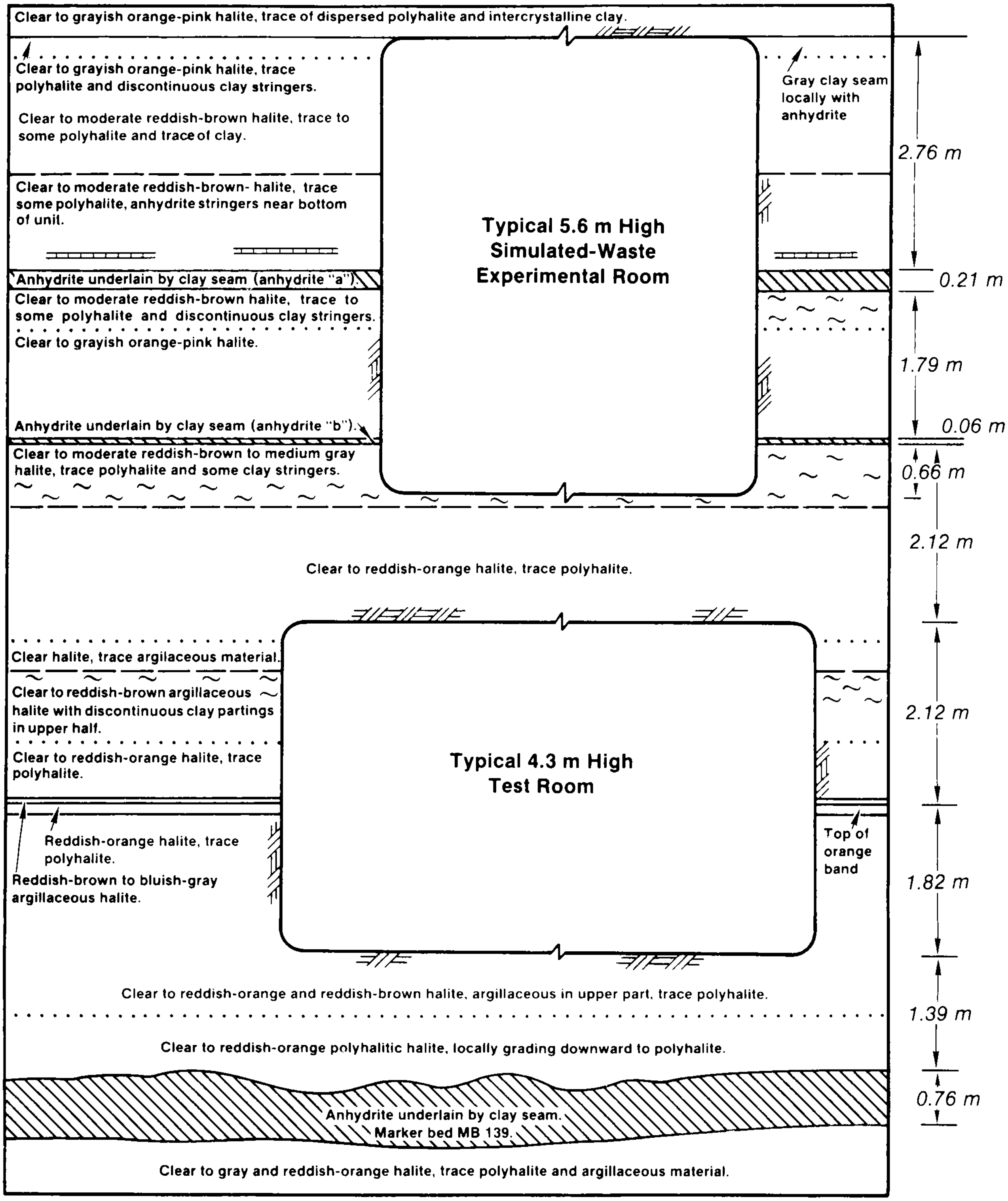

Figure 3.2. WIPP Facility Stratigraphy.

4. FUNDAMENTAL SEALING CONCEPTS

The basic goal of the sealing system is to minimize the release of radionuclides from man-made penetrations in the WIPP by limiting fluid migration in, through, and out of the repository (Stormont, 1984).

The most challenging aspect of seal[a] design is the requirement that it be effective for hundreds to thousands of years, greatly exceeding common engineering and construction demands or experience. Processes will have to be modeled well beyond periods of time for which direct observations can be made. Therefore, extrapolations of relatively short-term data using time-dependent models (whether simple or sophisticated) is inherent in the seal design process.

There are a number of factors which serve as the foundation on which designs are based. These include (Stormont, 1984):

- The consolidation of crushed or granular salt. This material, which is a by-product of mining the repository, is expected to consolidate into a mass comparable to intact salt under appropriate conditions, restoring the excavation to a condition approaching its undisturbed state. Seal designs incorporate crushed salt as the principal long-term seal material.
- The time-dependent plastic behavior of the host salt. Salt creeps or flows under deviatoric stresses, which results in the time-dependent closure of the excavations and the "healing" of fractures under some conditions. Intact salt also possesses a low permeability.
- Emphasis on the chemical and mechanical compatibility between the host formation and the seal in order to increase long-term stability of the seal system, reduce the burden on predictive modeling, and add confidence to long-term waste isolation. The use of crushed salt maximizes compatibility in the salt formation.
- Multiple component seal systems. A multiple component seal design allows individual seal components to serve different functions, to be effective over different time spans, and to exist in different locations and formations in order to ensure sufficient redundant barriers are in place at all times.
- Designs are to be practical. Some of the seal system will be emplaced by commercial contractors and the chance for success will be increased by the simplicity of the designs, and by utilizing modifications of and extrapolations from current industrial capabilities.

The seal systems for the WIPP can be grouped into shaft seals, panel entryway seals, non-waste room backfill, and borehole seals. Because the requirements, functions, and designs of these subsystems differ, they are considered as separate entities in this report. The backfill for the waste-containing rooms is presently not considered part of the sealing system.

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[a] Seals are not implied, defined or considered to be completely impervious structures. "Perfect" seals may not be practical or attainable, they are not verifiable, and they will undoubtedly not be necessary--as indicated by previous consequence assessments (Stormont, 1984).

5. SEAL FUNCTIONS AND REQUIREMENTS

In order to develop a rational seal design, quantitative requirements for seal system performance must be known. At this stage of assessment, specific requirements for sealing the WIPP have not been established. In this chapter, a perspective for how well the WIPP needs to be sealed is developed from estimates of seal functions and requirements.

The required performance of the seal system and its components must ultimately be developed from the performance assessments of the WIPP site system. These assessments will evaluate the system response of the repository to various scenarios and conditions and will compare the predicted radioactive releases to the applicable environmental standards. As these performance assessments are not yet available, the preliminary designs and design concepts considered here have been developed in the absence of quantitative performance requirements. However, some insight may be gained by considering the scenarios which have been developed for possible site performance assessments. Other factors, including the design philosophy for long-term waste isolation and binding agreements with the State of New Mexico, also contribute to present estimates of seal functions and requirements. In order to quantify seal performance requirements, a working criterion pertaining to effective salt consolidation has been developed. This criterion allows relevant seal design analyses to be conducted for both salt and nonsalt seal components.

5.1 Seal Functions and Requirements Inferred from Site Performance Assessment Scenarios

Following Hunter's scenario development work for the WIPP site (Hunter, 1987), seal performance may be considered in the context of two classes of scenarios: the "undisturbed" scenario and various human intrusion scenarios. The undisturbed scenario involves the predicted response of the disposal system without disruption by human intrusion or unlikely natural events. The human intrusion scenarios involve the disposal system response to the drilling of exploratory boreholes at the repository site, some of which provide fluids for the dissolution of waste or a pathway for the transport of radioactivity to the biosphere.

5.1.1 Undisturbed Scenario

The undisturbed scenario involves numerous time-dependent processes which will impact the performance of the entire repository, and the seal system in particular. Predominant processes identified to date include:

- Closure of the excavations in the halite formations. This closure tends to densify and consolidate backfills, and induces buildup of stresses in the vicinity of stiff seal components.
- Brine influx from the host rock salt into the excavations in halite formations. This naturally-existing brine seeps into excavations and, given enough time, will accumulate in the void spaces remaining in the excavations. The brine may affect backfill consolidation, corrode waste packages, and, if present in discrete pockets, become pressurized in response to closure.
- Water inflow from the water-bearing zones overlying the salt vertically down the shafts. The amount and rate of water inflow presently observed is governed by the performance of the shaft liners, but ultimately will be

dependent on the performance of the shaft seal system. In addition to the possibly deleterious effects of brine mentioned above, this water, being unsaturated in halite, may dissolve substantial quantities of salt.

- The creation of a disturbed zone surrounding excavations. The potential for flow in these zones can be significantly greater than in the undisturbed rock, and seal bypass can occur.
- Gas generation by the waste. This gas may accumulate in waste rooms, potentially slowing room closure and backfill consolidation.

The undisturbed scenario includes these processes, and their synergism and extrapolation to long periods of time. There is presently sufficient uncertainty associated with this scenario that a wide range of site performances can be postulated depending basically upon the efficacy of the sealing systems. Hunter (1987) proposed an undisturbed scenario that will be evaluated for its potential to provide a radioactive dose to members of the public. First, water from leakage through the shafts or from the Salado formation into the repository is postulated. Water in contact with the waste then dissolves radioisotopes, producing a solution of radioactive brine that occupies the remaining available void space in the repository. The continued closure of the excavations may then pressurize the brine pockets if they exist and force fluid from the repository through available paths to the biosphere. Possible paths are through the host rock (salt and/or clay and anhydrite seams) and the shaft seal system.

In such a sequence of events, if the sealed shafts are substantially more permeable than the formation, they may be preferential paths for water movement. The amount of water they can allow in and out of the repository and not violate the applicable standards will be the subject of the eventual performance assessments. Effective panel seals separating volumes of waste from one another and from the shafts will also provide substantial resistance to flow through the repository and therefore represent another significant barrier to waste release. Non-waste drift backfills would eventually serve a function similar to that of panel seals after sufficient reconsolidation.

A variation of the undisturbed scenario that could result in the release of radioactivity from the repository involves existing boreholes, which would serve as the source of water and/or the path for contaminated brine. No existing boreholes penetrate the repository, so they are inconsequential unless they facilitate introduction of water to the repository. To do so, the flows established in the boreholes must dissolve the salt that separates the borehole and the repository. In boreholes that intersect the water-bearing strata only above the repository there is no circulation of water, consequently the dissolution is controlled by diffusion and proceeds so slowly as to pose no threat to the WIPP even if the boreholes remain open (Stormont, 1984). Boreholes connecting water-bearing strata above and below the repository can dissolve salt faster because of the circulation established between them. Conservative calculations reveal that open boreholes of this type 300 m horizontally from the bounds of the repository will not intercept the repository for millions of years (Stormont, 1984). Sealing will further slow or prevent flow in the boreholes.

5.1.2 Human Intrusion Scenarios

Numerous scenarios that involve human intrusion can be postulated. The

Environmental Protection Agency (EPA) regulations suggest that future inadvertent intrusion by exploratory drilling for resources can be the most severe scenario assumed in a performance assessment (US EPA, 1985). These exploratory boreholes, assumed to be drilled between 100 and 10,000 years after the decommissioning of the repository, can be combinations of holes that may or may not penetrate the repository and/or intercept pressurized brine reservoirs or other water-bearing strata underlying WIPP. The boreholes that do not penetrate the repository may serve as shortened flow paths between the repository and the overlying water-bearing zones (Hunter, 1987).

When a borehole intercepts the repository, the conditions and properties existing in the repository at the time of intrusion will govern the resulting response. Depending on the condition of the waste and surrounding backfill, radioactive cuttings and drilling mud may be released to the surface, or the penetration may go undetected. Continued drilling into underlying strata may allow the introduction of pressurized brine into the repository. Panel seals will limit effect to one panel and will isolate this panel from subsequent intrusions in other panels. In addition to the possibility of future boreholes penetrating the affected waste panel(s) and allowing releases, contaminated brine leaving the repository through the shaft seal system must be considered.

In the human intrusion scenarios, the panel seals may have a role in limiting the consequences of intrusions by isolating volumes of waste from one another. The shaft seals have not been explicitly included in these particular scenarios. However, because the condition of the repository is in part dependent on the performance of the shaft seals, their performance is implicitly included in all the scenarios.

5.2 Discussion of Seal Functions and Requirements

Consideration of hypothetical scenarios that may result in radioactive releases to the public provides some concept of seal requirements. Shaft seals may be required to limit the volume of water introduced to the repository from the overlying water-bearing zones. A further requirement may be to limit the amount of contaminated brine that could move up the shaft to either the surface or the overlying water-bearing zones. Regardless of human intrusion scenarios, shaft seals will require a relatively rigorous design because: (1) shafts serve as a direct connection between the overlying water-bearing zones, the surface, and the repository; (2) shaft seals have to perform immediately after installation to limit the inflow; (3) shaft seals experience decreasing benefit from creep in the upper portions of the shafts; (4) shaft seals must be effective in the diverse geologic conditions through which the shafts pass; and (5) there is a limited opportunity for full-scale experimental design validation.

The role of the panel seals is less obvious. Their performance may not be required unless the repository is breached by future exploratory boreholes, at which time they will serve to isolate volumes of waste from one another and the shafts. However, their contribution as a redundant barrier should not be overlooked, especially because the results of direct experimentation and observation are available.

The necessity for non-waste drift backfill is not immediately obvious from the previously considered scenarios. However, regardless of the scenario, non-waste drift backfill will serve as a redundant barrier to fluid migration, limit damage around excavations, shorten the time until the repository is returned to a condition comparable to intact rock, limit subsidence and its accompanying effects, and serve as a disposal location for mined salt.

The requirements for seals in existing boreholes are expected to be minimal. Conservative calculations reveal that even open existing boreholes would not be expected to result in a significant radiological dose to the public basically because they do not penetrate the repository.

Because the performance assessment activity is not complete, new scenarios or processes may conceivably arise that place more or different requirements on one or more component of the seal system. Furthermore, regardless of the outcome of the performance assessments, the WIPP should be sealed to the extent deemed effective and practical at the time of decommissioning because (Stormont, 1984):

- o A cautious and conservative approach is appropriate when public health and safety are involved
- o Sealing will add confidence in the long-term isolation of waste, and reduce public concern regarding long-term hazards
- o Sealing the penetrations is consistent with the multiple barrier approach mandated by EPA standards.

Finally, the Department of Energy and the State of New Mexico have entered into a binding agreement that requires the inclusion of certain seals in the WIPP: "DOE shall use both engineered and natural barriers to isolate the radioactive waste after disposal in compliance with the Environmental Protection Agency standards. The barriers shall include, at a minimum, properly designed backfill, plugs, and seals at the drifts and at panel entries, and plugs and seals in the shafts and drill holes" (US DOE and State of New Mexico, 1981). Thus, there is a legal DOE commitment to seal the WIPP in addition to technical considerations and EPA standards.

5.3 Working Criterion

In order to conduct meaningful analyses in the absence of final performance requirements derived from site performance assessments, a preliminary "working" criterion is required. For this purpose, the preliminary design criterion has been defined as the requirement for effective crushed salt consolidation at panel entries and in portions of the shafts. A crushed salt criterion was selected because it is the fundamental element of the long-term sealing strategy: if salt consolidates to a condition comparable to the intact salt, the result is considered to be the ultimate long-term seal. Further, salt consolidation analyses embody many of the repository's time-dependent processes and will provide an opportunity to model these processes. A consolidated salt seal design criterion also permits requirements for other seal components to be estimated by determining the time and degree of isolation from water necessary to allow crushed salt to consolidate effectively.

The criterion is considered satisfied when the porosity of the crushed salt decreases to 5 percent or less. Available data suggest that as the porosity decreases to about 5 percent, the permeability of the crushed salt is reduced to submicrodarcy values (Holcomb and Shields, 1987; IT Corp., 1987). Such a low permeability makes the crushed salt a relatively good barrier to fluid flow. In fact, at this porosity the permeability of the crushed salt approaches that of intact salt. Thus, this preliminary criterion is probably conservative, as future requirements cannot reasonably require a seal system to have a lower permeability than the intact host rock. The 5 percent specification has an important practical application. The present constitutive model for crushed salt consolidation indicates that the crushed salt will offer very little resistance to the continued closure of the excavations until the porosity of the crushed salt decreases to 5 percent or less (Sjaardema and Krieg, 1987). Thus, as an analytical convenience, drifts and shafts containing crushed salt backfill can be modeled as open drifts until they become effective seals.

Obviously, the estimated time required for the crushed salt to achieve satisfactory consolidation is of interest. Also important is the time and condition (porosity) at which the crushed salt becomes saturated with water liberated from the intact salt or with that flowing along the penetration. The water in the pore space could resist or retard further consolidation, and if the porosity is greater than 5 percent, significant connected porosity may persist. If so, the partially saturated crushed salt could become a preferential flow path, degrading a component of the long-term sealing strategy.

A design criterion that involves salt consolidation allows requirements for other seal components to be inferred. The principal function of most non-salt seals is to limit the amount of water that reaches the crushed salt while it's consolidating. As will be subsequently discussed, present estimates of times to achieve effective salt consolidation are <100 years at the disposal horizon and in the lower portions of the shafts. Given the present inability to predict durability or longevity for seal materials other than salt, limiting the timeframe for the required performance of these seals to periods within reasonable engineering experience is crucial for the credibility of the design. In addition to the need for other seal components to protect salt during consolidation, other seal materials are included in seal designs because: (1) crushed salt will not be consolidated by creep closure in those portions of the shafts which pass through nonsalt formations; (2) crushed salt is not an effective short-term barrier; (3) other seal materials may have desirable properties not possessed by crushed salt; and (4) redundancy in the design can be provided by including other seal materials.

6. CANDIDATE SEAL MATERIALS

Following is a discussion of the various candidate seal materials: salt, bentonite, cementitious materials, and asphalt. The best possible seal material would return a penetration to a condition comparable to its undisturbed state within a predictable period of time.

6.1 Salt

Salt has the potential to be an effective, simple seal material. Experimental evidence suggests that granular or crushed salt consolidates under certain conditions, resulting in a porosity and permeability that decrease toward values comparable to intact salt. For crushed salt emplaced in an opening in a rock salt formation, the consolidation is driven by the creep closure of the adjacent host rock.

The time-dependent properties of crushed salt have been measured by numerous laboratory researchers. At a given stress, the single most important parameter in the consolidation of crushed salt is the presence of a small amount of water. Small amounts of water accelerate consolidation and the accompanying permeability decreases in comparison with dry crushed salt (Holcomb and Shields, 1987; IT Corp., 1987; Shor et al., 1981; Pfeifle and Senseny, 1985). The effects of other variables, such as particle size, are secondary and not as obvious.

The dependence of salt consolidation on added water can be illustrated by considering the experimental results of Holcomb and co-workers (Holcomb and Hannum, 1982; Holcomb and Shields, 1987). The 1982 tests were conducted on dry (no additional water) crushed salt, whereas the 1987 tests involved small amounts (<3% w) of additional water. The volume strain data, dV/V_0, from both sets of data can be reasonably described by (Holcomb and Hannum, 1982; Holcomb and Shields, 1987)

$$dV/V_0 = a \log t + b \qquad (1)$$

where a and b are fitting constants and t is time in seconds. The constant, b, is a measure of the initial condition of the sample (Holcomb and Shields, 1987). To compare times to achieve the same volumetric strain for tests under similar initial and loading conditions, Equation (1) can be rewritten as

$$t_2^{(a_2/a_1)} = t_1. \qquad (2)$$

The constant, a, for wet test data is five to ten times greater than from a comparable dry test. Therefore, for dry crushed salt to experience the same strain under similar test conditions requires a time five to ten orders of magnitude greater than that for the wet sample.

Sjaardema and Krieg (1987) developed and implemented a constitutive relationship for the consolidation of crushed salt based on the laboratory data of Holcomb and co-workers. Numerical calculations of wet crushed salt consolidation in WIPP shafts and drifts were then conducted to determine the influence of the presence of the crushed salt on the closure of the shafts and drifts. Up to a fractional density of 0.95 (the extent of the laboratory data the model was based on), the results indicate that no substantial backstress (resistance) develops in the crushed salt. That is, the closure is largely unaffected by the presence of crushed salt.

As expected, as consolidation proceeds, the permeability of the crushed salt decreases. In general, permeability values for samples with a fractional density of 0.85 or less are millidarcy or greater values (10^{-15} m^2

or greater). Between fractional densities of 0.85 and 0.95, however, the permeability drops dramatically. By 0.95 fractional density, the permeability of the crushed salt is on the order of that of intact salt. Figure 6.1 shows permeability versus fractional density for two tests that proceeded to high fractional densities (Holcomb and Shields, 1987; IT Corp, 1987). A similar trend of a dramatic permeability decrease at 0.95 fractional density has been observed in experiments on calcite to simulate the alteration of permeability and porosity of rocks by plastic flow processes (Evans, 1983).

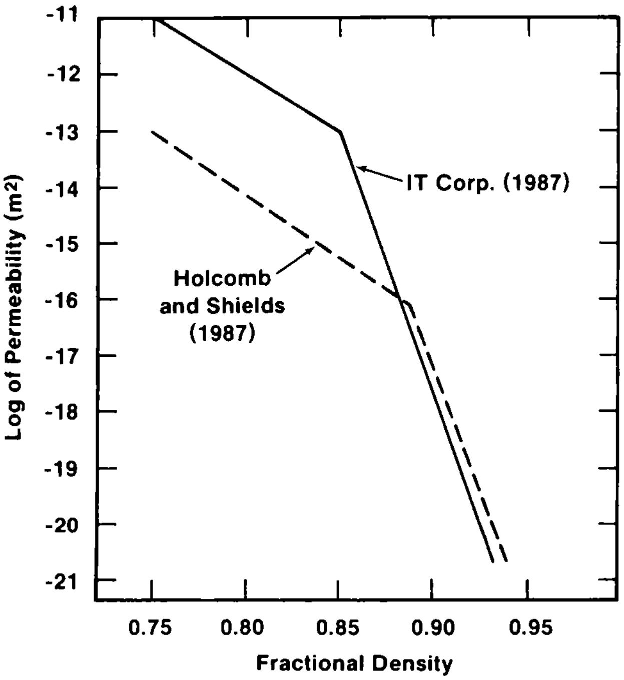

Figure 6.1. Permeability Versus Fractional Density for Two Consolidation Tests on Wetted Crushed Salt.

The exact mechanism(s) of consolidation are not understood. Clearly, water plays some important role. Yost and Aronson (1987) dismiss dislocation mechanisms of creep as a primary mechanism of consolidation of wet salt, and suggest pressure solution and/or the Joffe effect as the dominant mechanism(s). Holcomb and Shields (1987) discuss the possibility of a pressure solution mechanism for consolidation in view of their experimental data, and conclude that further investigation is required. Post-test analyses were conducted on consolidated samples (IT Corp, 1987), and it was concluded that water played an important role in salt consolidation (and the accompanying permeability decrease) by facilitating pressure solution. Zeuch (1987) adapted a model for isostatic hot-pressing to the consolidation of nominally dry crushed salt, and found good agreement between the model and Holcomb and Hannum's laboratory data. Interestingly, this model predicts consolidation approaching intact salt densities over periods of less than 50 years under approximate repository conditions, in contrast to simple extrapolations of laboratory data. The model is presently being expanded to include the influence of water.

While small amounts of water have been determined to benefit consolidation, larger amounts may be detrimental. It is conceivable that if the salt becomes saturated while substantial porosity remains, further consolidation could be impeded by the low compressibility of the entrapped brine (Nowak and Stormont, 1987). Previous tests by Baes et al., (1983) indicate that brine can be readily squeezed out of salt so as to not impede consolidation even to low permeabilities. Preliminary results by Zeuch (1987) suggest that saturated crushed salt consolidates similarly to crushed salt with much less water. However, these laboratory tests have been on vented samples; it is not obvious to what degree brine in large emplacements will be expelled during consolidation.

Another advantage of crushed salt is its availability and low cost. Granular salt is a by-product of the excavation of the WIPP Facility, and is therefore in plentiful supply. Future operations may wish to consider underground stockpiling to limit handling of the mined salt.

Because the time required for crushed salt to become an effective seal is dependent on its initial density, the emplacement method can have a large impact on the sealing function. The options for emplacement include dumping, dumping with compaction via vibrating tampers or rubber-tired trucks, pneumatic stowing, or the placement of pre-compacted blocks. With the exception of the blocks, commercially-available equipment exists for these emplacement techniques. Based on adobe technology, Sandia has developed a prototype machine that presses blocks of salt (and other materials) for use as a seal material (Stormont and Howard, 1987). For the possible emplacement techniques mentioned above, a reasonable range of fractional densities is from 60 to 85 percent. The 60 percent fractional density was obtained from crushed salt poured into molds in the laboratory (Holcomb and Hannum, 1982). The 85 percent fractional density is achievable with the Sandia Block Machine (Stormont and Howard, 1987). Interestingly, it was necessary to add 1 to 3 percent water to produce coherent blocks. Block properties are given by Gerstle and Jones (1986) and Stormont and Howard (1987).

An alternative to crushed salt as a seal material is intact or quarried salt blocks. These intact blocks have higher fractional densities than pre-compacted blocks of granular salt, and the time required for them to become an effective seal is correspondingly reduced. The permeability decrease expected in a quarried salt seal as the adjacent rock tends to creep in may be similar to the "healing" of salt samples brought to the laboratory from the field. Initial permeabilities are relatively great due to sampling damage; after application of hydrostatic pressure for only a short period of time, permeabilities decrease to low values (Sutherland and Cave, 1980). The interfaces between blocks may heal readily, as evinced by fracture healing studies in salt (Costin and Wawersik, 1980; IT Corp, 1987). Salt is easy to cut and machine, and blocks have already been fashioned from 41 cm diameter cores simply using a band saw. Seals constructed of intact salt blocks require stock material, and block machining would be labor intensive; therefore these alternatives are presently envisioned for limited applications where time to effect a salt seal must be minimized.

6.2 Bentonite

Clays have found many applications as fluid barriers in underground excavations (e.g., National Coal Board, 1982; Sitz, 1981), as components of earth dams (e.g., Sima and Harsulescu, 1979), and in containment of hazardous wastes (e.g., Johnson et al., 1984; Leppert, 1986). In particular, sodium bentonite is under consideration as a seal material for geologic nuclear waste repositories (e.g., Pusch, 1987; Stormont, 1984; Lopez, 1987; Kelsall et al., 1982). Bentonites are composed principally of montmorillonite, a smectite mineral responsible for their characteristic swelling. Bentonite mixed with filler or ballast material is being considered as a seal material as a matter of economy, as well as to minimize the loss of the bentonite through small fractures or cracks. Sitz (1981) found that the sand in a bentonite/sand mixture stopped bentonite losses through fractures with a maximum width of 2 to 4 mm.

The permeability of mixtures of bentonite and various filler materials has been measured by numerous investigators in the laboratory (e.g., Radhakrishna and Chan, 1985; Wheelwright et al., 1981; Peterson and Kelkar, 1983; Stroup and Senseny, 1987). There is considerable variability in the data due to differences in test methods, sample density, working fluids, etc. In general, the permeability of the mixtures to water and brine was found to fall off to microdarcy or lower values somewhere between 25 to 50 percent bentonite by weight, probably coincident with the bentonite becoming the continuous phase of the mixture (Nowak, 1987). Pusch (1987) determined that the permeability of bentonite to brine is about an order of magnitude greater than that to fresh water.

Another important property for mixtures containing bentonite is the swelling pressure developed when the mixture is confined and saturated with water. Swelling is expected to fill voids and heal fractures within the bentonite seal and perhaps to a limited degree in the adjacent host rock. The average swelling pressure of confined 100 percent bentonite in salt water was given by Pusch (1980) as

$$p_s = e^{11.5(rho-1.87)} \text{ (MPa)} \qquad (3)$$

where p_s is the swelling pressure and rho is the bentonite bulk density between 1.8 and 2.1 g/cc. Gray, Cheung, and Dixon (1984) demonstrated that swelling pressures of bentonite mixtures are dependent on the effective clay density, that is, the mass of the bentonite divided by the volume of the bentonite and any voids. Thus, the sand or other filler material is merely an inert filler.

Bentonite/sand or bentonite/salt mixtures could be emplaced in much the same way as crushed salt: mechanically, pneumatically, or in pre-compacted blocks. Blocks of 50 percent bentonite/50 percent salt and small amounts of water have been pressed to a dry density of about 1.97 g/cc, and an effective clay density of 1.6 g/cc (Stormont and Howard, 1987). At these conditions, a swelling pressure of about 2 MPa and a brine permeability of about 10^{-19} m^2 are expected. Drift emplacements of bentonite mixtures in the Stripa Facility were accomplished with vibrating tampers and a robotic pneumatic machine (Pusch, 1987). Bentonite has also been emplaced and tested as a borehole seal (Pusch, 1987; South and Daemen, 1986; Kimbrell, Avery, and Daemen, 1987). Bentonite slurries have been suggested as a rock mass grouting material (Meyer and Howard, 1983).

Soil structures (including clays) can fail in the presence of seepage by erosion along pre-existing cracks or piping (internal retrogressive erosion). The predominant factors involved in failure by both mechanisms are (Resendiz, 1976) loosening of interparticle coherent forces upon saturation (dispersivity), permeability, and swelling potential. The risk of failure is increased as the first two factors increase and the third decreases. Clays rich in montmorillinite (e.g., bentonite) are generally too expansive to permit cracks to remain open and too impervious to allow seepage velocities large enough to induce piping (Resendiz, 1976). Further, bentonite is relatively plastic and can withstand considerable deformation prior to failure. The tendency for erosion or piping failures is increased at the interface between the clay and dissimilar materials (Penman and Charles, 1979), i.e., the seal/rock interface. Pusch, Borgesson, and Ramquist (1987) demonstrated the effectiveness of bentonite in effecting a tight interface by swelling. Pusch (1983) investigated the possibility of the migration of bentonite into rock fractures, and the subsequent erosion of the bentonite by flowing groundwater. He concluded that bentonite will migrate a few tenths of meters into fractures wider than 0.1 mm over the course of thousands of years, and should not be significantly eroded by groundwater. Because swelling is a time-dependent phenomenon, the rate of introduction of water prior to saturation may be significant. Stormont and Howard (1987) emplaced and tested 50 percent bentonite/50 percent crushed salt seals in 1 m diameter boreholes in the WIPP Facility. Failure by erosion was observed when water was introduced rapidly to one face of the seal; a relatively low permeability seal was established in a similar seal configuration when the water was introduced at a slower rate to permit a gradual uptake of water.

Clays exist naturally in geologic formations, including bedded salt, and are therefore appealing as long-term seal components. Clay sealants have been used by man for long periods of time; Lee (1985) documented the effectiveness of a clay sealant for periods as long as 2100 years. While bentonite alteration to other clays does occur under some conditions, at non-elevated temperatures bentonite transformations are expected to be very slow, on the order of millions of years (Meyer and Howard, 1983; Roy, Grutzeck, and Wakeley, 1983). Krumhansl (1984) found from experiments in WIPP-specific aqueous solutions that bentonite is expected to maintain its desirable mineralogic characteristics indefinitely.

6.3 Cementitious Materials

Cementitious materials have been considered as a candidate repository seal material because (Lankard and Burns, 1981): (1) cementitious materials possess favorable seal properties such as low permeability and adequate strength; (2) there is a historical precedent for sealing penetrations with cementitious materials; (3) much physical and chemical properties data exist; and (4) construction with cementitious materials is an established practice with a large number of equipped, qualified and available commercial contractors. Since 1975, cementitious seal materials have been developed and studied for the WIPP. Early work focused on development of grouts for borehole sealing, with more recent research being devoted to concretes for sealing shafts and drifts. Research on rock fracture grouting has been initiated for the WIPP.

6.3.1 Grouts

Cementitious grouts have been utilized for many years to seal surface-drilled wellbores for disposal of chemical and toxic wastes and to seal abandoned oil and gas boreholes. Typically, few problems are encountered but quantative measures of seal effectiveness are generally not available (South and Daemen, 1986). Emplacement technology for borehole sealing with cementitious grouts is available (e.g., South, 1979). Recent testing has provided more information about the effectiveness of cementitious borehole seals. The Bell Canyon Test, conducted in borehole AEC-7 near the WIPP site, involved the placement of a 2-m-long grout seal at a depth of 1370 m in anhydrite host rock, isolating the upper portions of the borehole from the 12 MPa Bell Canyon aquifer. The plug reduced the production of the aquifer by five orders of magnitude, and analyses indicated that the predominant flow occurred through the plug/borehole interface region (Christensen and Peterson, 1981). In situ tests in granite show that cementitious plugs placed with conventional methods reduce the hydraulic conductivity of the wellbore to or less than that of the host rock (Kimbrell, Avery, and Daemen, 1987).

Laboratory tests by South and Daemen (1986) indicate the effectiveness of cementitious grouts as a seal material in basalt, granite and tuff. Large flows along the interface have been observed during a laboratory test on a grout-sealed hole in anhydrite (Bush and Lingle, 1986); the sealing effect of a grout plug in rock salt was considered to be much better in a companion test (Bush and Piele, 1987).

Gulick and Wakeley (1987) provide the reference formulations and properties for candidate grouts for use in sealing the WIPP. Both a freshwater (BCT-1FF) and saltwater (BCT-1F) grout have been selected. A saltwater-based grout is necessary in the host rock salt to preclude dissolution of adjacent rock during hydration. The properties of the freshwater grout are considered somewhat more favorable. The BCT-1FF has been emplaced in the Bell Canyon Test, in portions of the C&SH shaft liner, in the upper portions of borehole B-25 on the WIPP site, and in an underground test bank for curing candidate seal materials (the Plug Test Matrix). The BCT-1F mixture has been emplaced in borehole B-25 and in the Plug Test Matrix. The properties of the BCT-1F and BCT-1FF grouts have been determined under a range of conditions, and are summarized by Gulick and Wakeley (1987). Subsequent to the development of the BCT grouts, modifications have been proposed (e.g., Wakeley, Walley, and Buck, 1986; Buck, Boa, and Walley, 1985; Buck, 1985; Buck et al., 1983; Wakeley and Roy, 1985). However, because there is no identifiable deficiency of the BCT grouts and the advantages of the other formulations have not been shown, the BCT grouts remain the reference materials for the WIPP.

Another potential use of cementitious grouts in sealing the WIPP is grouting fractures in the host rock. Grouts for this application are expected to be thinner than the BCT grouts. Control of inflow to the existing WIPP shafts has been attempted in part by rock grouting with cementitious mixtures. Rock grouting with cementitious mixtures has been used to control inflow to shafts (e.g., Hart, 1983), in conjunction with establishing concrete seals in shafts and drifts (e.g., Auld, 1983; Garrett and Pitt, 1958; Garrett and Pitt, 1961), and with dams. The complicated system of a curing grout injected into poorly characterized fractures has generated a technology laden with empiricism (e.g., Dept. of the Army, 1984) and controversy over techniques and claims of effectiveness. Rock fracture grouting may be detrimental in some instances: fractures may propagate from injection pressures, and water pressure buildup from sealing drainage paths may be sufficient to further fracture the host rock. Schaffer and Daemen (1987) considered rock fracture grouting technology for repository sealing applications, and concluded that "considerable and well-recognized uncertainty exists about the actual performance of grouting."

6.3.2 Concretes

Concrete has historically been used as a seal and shaft liner material because of its availability, relatively low cost, and familiarity among contractors and mine operators. Furthermore, properties of standard concretes such as strength and permeability are generally understood and considered adequate for typical seal applications (National Coal Board, 1982; Auld, 1983). Unfortunately, there is little documentation of the design and performance of concrete seals. The few references to concrete seals in the mining industry must be considered in the context of their application: these seals are usually emplaced in response to an inrush of water, and a substantial reduction in leakage is considered success. In what is believed to be the only documented tests on experimental full-sized drift seals, Garrett and Campbell Pitt (1958, 1961) demonstrated the effectiveness of concrete seals as fluid barriers in quartzite host rock. Auld (1983) cites examples of the successful placement and performance of concrete seals in a sandstone and a gypsum and marl deposit. Sitz (1981) provides a summary of German experiences with concrete seals in various rock types, describing both successes and failures of concrete seals. Concrete seals have been successfully utilized in tuff as containment structures for underground testing at the Nevada Test Site (Gulick, 1987).

The single consistent conclusion from historical experience is that concrete itself is relatively impermeable, and that observed leakage is predominantly attributable to the concrete/rock interface and the near-field rock. Probable causes for flow at the interface are concrete shrinkage, poor rock quality, and interaction between the concrete structure and the host rock. In non salt host rock, there are two potential remedies to ensure a tight interface: the use of an expansive concrete and contact or interface pressure grouting. Expansive concretes have been developed in the laboratory (e.g., Buck, 1985); however, experience with placement of numerous full-size drift seals in tuff with supposedly expansive concretes is inconclusive with regard to net expansion (Gulick, 1987). Pressure grouting along the concrete/rock contact has been demonstrated to be effective in substantially reducing the leakage along the interface, and is considered standard practice in the placement of concrete seals (Garrett and Pitt, 1958; Garrett and Pitt, 1960; Auld, 1983; National Coal Board, 1982; Gulick, 1987; Defense Nuclear Agency). In halite, creep of the adjacent host rock may result in a tight rock/concrete interface.

Reference formulations and properties of candidate concretes for the WIPP are given by Gulick and Wakeley (1987). A saltwater-based concrete (ESC) and a freshwater concrete (FWC) were selected. The ESC is an expansive (in laboratory tests), salt-saturated concrete which has been emplaced in two seal tests in the WIPP (Stormont, 1986; Stormont and Howard, 1986) and in the Plug Test Matrix. The performance of the ESC material has been adequate structurally (Stormont, 1987; Labreche and Van Sambeek, 1987) and exceptional as a fluid barrier (Peterson, Lagus, and Lie, 1987b) in the field tests. Its properties have been extensively tested in the laboratory and are given in Comes et al. (1987), Wakeley and Walley (1986), and Wakeley (1987). The FWC is based on an expansive concrete developed by Buck (1985) for nonsalt host rock applications.

A thermomechanical model for the ESC was developed based on the results of the in situ seal tests (Van Sambeek and Stormont, 1987; Labreche and Van Sambeek, 1987). The model results show excellent agreement with the measured temperature changes from hydration and fair agreement with the measured strains and stresses in the seal and the adjacent rock. The assumed expansivity of the concrete was found to be the parameter that influences the short-term model results the most and is the least well understood. Numerical modeling of panel seals has utilized the elastic properties of the ESC (Arguello, 1987; Arguello and Torres, 1987); both the ESC and FWC time-dependent properties have been applied to numerical studies of shaft seals' structural interactions and stability (Van Sambeek, 1987).

Large volume pours of concrete will be required for drift or shaft seals. This existing emplacement technology uses standard commercial equipment and techniques (e.g., Defense Nuclear Agency). In situ seal tests conducted at the WIPP have successfully employed gravity-feed by tremmie for small-scale shaft seals and pumping into a formed interval for small-scale drift seals (Stormont, 1986; Stormont and Howard, 1986).

A principal concern regarding the use of cementitious materials as a seal material for nuclear waste repositories are their durability or longevity. Cementitious materials will not be in chemical equilibrium with their environment (Lambert, 1980a). Potential mineralogic phase changes could manifest themselves as: (1) the formation of a soluble, friable, or permeable phase in the plug or nearby rock; (2) shrinking or degradation of adhesion, opening the interface between the seal and the rock (Lambert 1980a, Lambert, 1980b). On the other hand, there is evidence for the longevity of cementitious materials in certain environments. Evaluation of some ancient cementitious materials reveals they have survived in apparently good condition for centuries (Malinowski, 1981; Monastersky, 1987). Research on the durability of cementitious mixtures applicable to the WIPP is generally favorable with regard to expectations or speculations about the maintenance of long-term properties (Buck, 1987; Wakeley, 1987b; Burkes and Rhoderick, 1983; Wakeley and Roy, 1986; Roy, Grutzeck, and Wakeley, 1983). Yet it is known that concrete is susceptible to degradation, especially in environments with high sulfate contents (Lea, 1971) such as Culebra formation water (Mercer and Orr, 1979). Hart (1983) reports that concrete liners which pass through the formations above salt mines in the northeastern U.S. degrade or corrode from formation water leaking through the liner, resulting in a reduction of the concrete thickness of about 3 mm per year. An examination of a 20-year old shaft liner in the Carlsbad potash district suggests that the concrete liner has appreciably deteriorated from sulphate attack (D'Appolonia, 1981). Heimann et al. (1986) demonstrated that the presence of clay accelerates the dissolution of some cements.

There is presently no comprehensive model of the complicated system of cementitious materials, the host rock, the formation water, and their interactions sufficient to make reliable predictions of long-term (thousands of years), time-dependent performance. Indeed, the problem is so multi-faceted, large, and diverse (involving kinetics, thermodynamics, and chemistry) that resolution of all issues seems remote. Therefore, reliance on cementitious materials as long-term seal materials should be minimized. Emphasis on consolidated salt as the long-term seal will relieve the requirement for concrete effectiveness to perhaps a few hundred years.

6.4 Asphalt

Asphalt is a bituminous material produced by the distillation of crude oil. In the construction industry, asphalts have a wide variety of applications because they are durable, highly waterproof, strong, and highly resistant to the action of most acids, alkalies and salts (Herubin and Marotta, 1977). Bacterial degradation requires microorganisms and moisture; even if these conditions are present, the degradation is expected to be very slow (ZoBell and Molecke, 1978). Many properties of asphalt, including density and viscosity, can be tailored by the distillation process and by the addition of weighting materials and blending and dissolving agents.

Liquid asphalt has been utilized as a key component in the construction of waterproof liners in strata overlying salt and potash deposits (Hart, 1983; Wegener, 1983). A method successfully employed in German mines is described by Wegener (1983). A precast concrete block liner is fixed to the rock concurrent with shaft construction. A steel cylinder is then emplaced in the shaft so as to leave a gap or annulus between the concrete blocks and the steel. A reinforced concrete liner is then cast on the interior of the steel cylinder. Finally, asphalt with a specific gravity 30 to 40 percent greater than water is poured into the annulus up to the surface, so asphalt tends to move out into the formation rather than formation water tending to move into the shaft. Asphalt is added at the surface to replace that which moves into the formation. Wegener (1983) reports that two such shaft liners recently installed are ". . . absolutely impermeable to the water from surrounding strata." Such a liner design is being used in the shafts of Germany's proposed radioactive waste disposal facility at Gorleben. Sitz (1981) describes the use of asphalt as a component of an elaborate seal for an underground gas storage facility in domal salt. Overpressure of the asphalt is achieved by pipes from the surface in contrast to an open volume of asphalt.

Solid asphalt, or asphalt cement, has also been used in waterproof liners and drift seals. The liner key is often located in the saliferous formation, and it is imperative that water does not flow behind it or the entire shaft liner may fail by washout or dissolution. Special care is taken to seal the liner at the key, including the use of asphalt cement (e.g., Wegener, 1983; D'Appolonia, 1981). Solid asphalt has also been used in conjunction with drift and shaft seals in salt or potash mines in Germany (Sitz, 1981).

Previous WIPP seal concepts have not included asphalt, and the experimental program has not evaluated asphalt as a candidate seal material. However, a large experience and data base exist from applications at other facilities and could be readily applied to the WIPP situation. Asphalt warrants consideration as a possible seal material based on its successful applications, especially in Germany. Its present role in WIPP seal concepts is as a potential redundant component.

7. DESIGN EVALUATION OF SHAFT SEALS

Shaft sealing strategy and designs are considered separately for the Rustler and Salado formations. Bentonite and concrete are the principal seal materials in the Rustler, where treatment of the disturbed rock zone may be the most difficult sealing problem. In the Salado, salt is the principal long-term seal material.

7.1 Shaft Sealing Strategy

The fundamental strategy for sealing the WIPP shafts is to maximize the amount of consolidated salt between the repository horizon and the top of the Salado Formation. In this way, the long-term seal is essentially identical with the host rock, and the otherwise very difficult issue of seal longevity is averted. Shaft seal performance can then be evaluated in the context of salt consolidation; that is, the time to achieve satisfactory consolidation can be used to estimate the type, number, and required performance of other seal components. Furthermore, effective salt consolidation achieved prior to 100 years after decommissioning is independent of breach scenario assumptions.

To ensure effective consolidation, unacceptable amounts of water must be prevented from accumulating in the crushed salt. There are three possible sources of water: the overlying water-bearing zones, the host rock salt, and the repository. Water, if present, could be forced up the shafts from the repository horizon by closure or by some breach event. This suggests a seal at the base of each shaft to eliminate a preferential flow path up the shafts prior to effective salt consolidation. Water influx from the host rock salt will be difficult to limit along the entire length of the shaft in the Salado Formation. An annular seal may limit the flow into the crushed salt, but it would be at odds with the fundamental strategy of monolithic salt as the long-term seal. The crushed salt could be protected from the overlying water-bearing zones by seals in the top of the Salado, seals in the lower portions of the Rustler, or both.

Placing seals in the lower portions of the Rustler is intuitively obvious, because these seals would be as close as possible to the source of water (the Culebra and Magenta dolomites, and possibly the Rustler/Salado contact). However, the Rustler lithology is very diverse, being composed of carbonates, sulfates (gypsum, andhydrite, and polyhalite), clastic rocks, and halite (US DOE, 1983; US DOE, 1984). Such variability may be troublesome if, for example, seal design requires a certain length of seal in the same rock type, or if a detailed understanding is needed of the interaction between the seal material and multiple host rocks. Some of the weaker rocks in the Rustler may be adversely affected by the excavation and subsequent redistribution of stresses, resulting in seal locations which are weak and a potential source of bypass. Further, some of the clastic rocks such as siltstones and sandstones in the Rustler are susceptible to erosion, which could result in relatively large flow along the seal/rock interface.

The Salado formation may be a more favorable environment for seals, because it has a more uniform stratigraphy and the stratigraphic units are thicker than the ones in the Rustler. The predominant rock type is halite, which has many properties considered favorable for sealing (low permeability, fracture healing, and plastic deformation). Moreover, the experience and data base for salt is large, because the vast majority of the seal tests are being conducted with halite as the host rock. The principal concern with sealing in the Salado Formation is the solubility of halite. The water of the Culebra and Magenta dolomites is not saturated with respect to NaCl and is therefore able to dissolve salt. Even brine which is saturated at standard conditions may be capable of dissolving salt due to the pressure and temperature dependence of salt solubility. Concern that the initial seepage behind WIPP waste and exhaust shaft liners could progress enough to threaten the stability of the liner keys (located in the top of the Salado) has led to remedial grouting programs in these shafts. In the waste shaft, drill holes that penetrated the liner/salt contact produced an estimated 0.03 m^3/hr (Sauliner and Avis, in preparation). In the exhaust shaft, pre-grouting activities indicated some fluids at the concrete/salt contact (US DOE, 1987). Salt dissolution behind liners in US Gulf Coast mine shafts requires more than half of all shafts to undergo maintenance (principally grouting) to preclude unacceptable inflows (Hart, 1983). Sitz (1981) reviews attempts to seal salt and potash mines in Germany, and concludes that "due to the solubility of the saliferous system, the greatest problems occur in the construction of plugs and dams in potash and rock salt mining."

The preceding discussion indicates that there are advantages and also problems to overcome in sealing either the Salado or the Rustler to limit inflow down the shafts into the crushed salt seals. A prudent approach is to not place total reliance on either system, but to include seals in both regions. This approach is consistent with the concept of multiple barriers.

7.2 Shaft Seals in the Rustler

A simple model of flow through seal systems in the Rustler was constructed by Stormont and Arguello (in preparation) to provide information relevant to shaft seal design. The model provides one-dimensional flow through the seal material, the seal/rock interface, and the adjacent rock (the so-called disturbed zone) at 14 intervals between the Magenta and the top of the Salado. Concrete and bentonite-based materials were input as the seal components. Also input were various cases of seal material and rock performance (principally permeability) estimated from available measurements. Combinations of seals with varying seal and rock performance were examined via the model, and the flow rate through the seal system was compared with estimates of allowable flow into the lower portions of the shaft in the Salado (the allowable inflow was based on a study of salt consolidation in the lower portions of the shafts, and is discussed further in Section 7.3). The analysis provided the following conclusions:

- The quality (essentially the permeability) of the rock adjacent to the seal is the single most important factor in maintaining a low flow rate through the seal system. Even with perfect sealing of the shaft itself, large flows bypassing the shaft seals through the adjacent rock are possible, especially if vertically persistent fractures exist.
- A very small gap at the concrete/rock interface can allow substantial flow through concrete seal systems.
- The assumed degradation of concrete seals may render concrete structures ineffective as flow barriers even when their initial permeability is low.
- Including bentonite in the seal design can obviate the above concerns over concrete seals if the bentonite is located in a low permeability host rock and does not appreciably degrade with time.

The conclusions from this study suggest that emphasis should be placed on establishing seals of low permeability and long-term durability against rock which has little potential for vertical flow or seal bypass. This approach is consistent with the undisturbed state of the Rustler: the rocks between the water-bearing zones and the top of the Salado have low vertical permeabilities (Saulnier and Avis, in preparation). Thus, the intent for seals in the Rustler is to reestablish the natural low permeability of portions of the formation. Bentonite-based seals, if adequately confined, should be satisfactory. Anhydrite and claystone are two potential rock types in which such a seal can be located. The low vertical permeability of the Rustler has been attributed in part to anhydrite (Barr, Miller, and Gonzalez, 1983). Anhydrite is a strong rock, and its disturbed zone may be limited and well defined. Claystone is more similar to the seal material than is anhydrite, and therefore increases compatibility. Low permeabilities have been measured in Rustler claystone within 2 m of the shaft wall (Saulnier and Avis, in preparation).

A schematic of the design concepts for sealing the Rustler is given in Figure 7.1. The principal seals are constructed from bentonite-based and cementitious materials. Above the top of the Magenta dolomite, the shaft with the existing liner left in place is filled with locally plentiful material, including a clay fraction to reduce the permeability of the mixture, if desired. Owing to the relatively high transmissivity of these strata, there is little motivation to establish a low permeability seal in this location. Between the Magenta dolomite and the top of the Salado are three bentonite-based seals that abut against anhydrite and claystone layers. These are the principal fluid barriers in the Rustler. Concrete in the shaft between the bentonite seals confines the bentonite, provides structural strength for the system, and acts as a redundant flow barrier. Grouting of the concrete/rock interface or contact is specified. Formation grouting is provided in some locations to seal disturbed zones adjacent to the shafts, where possible. It is expected that the shaft liner will have to be removed at locations adjacent to the bentonite seal locations to permit removal of damaged rock and prevent the degraded liner from becoming the predominant flow path through the seal system. Whether or not the rest of the liner can remain in place will depend on the function and shape of the adjacent seal and the condition of the

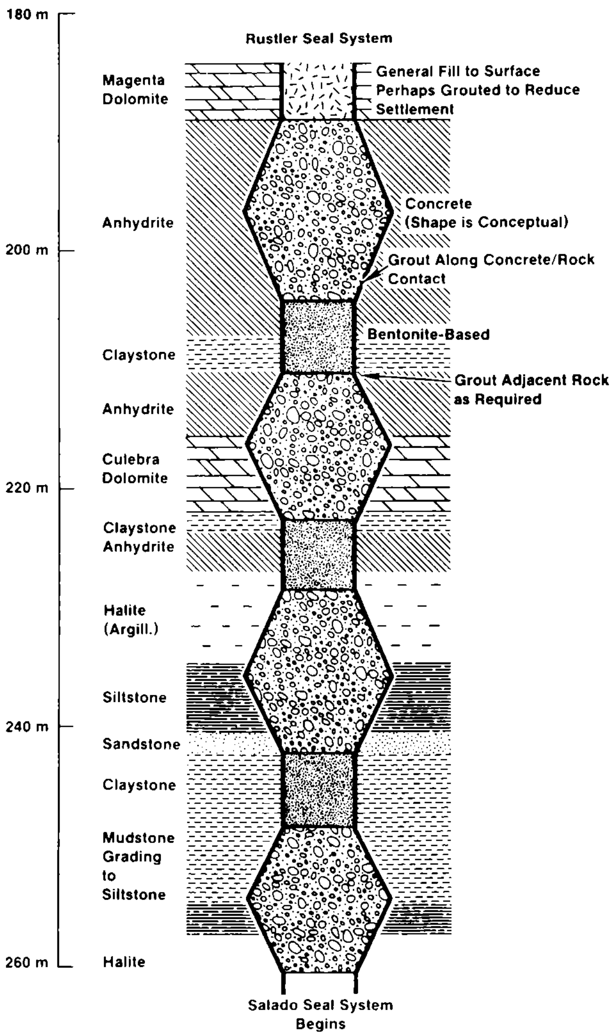

Figure 7.1. Schematic of Design Concepts for Sealing the Rustler.

liner. Note that there is no intent to establish a tight seal in the water-bearing zones themselves because this would require very extensive and difficult treatment (grouting the rock), which would probably divert the water around the seals into lower portions of the shafts.

7.2.1 Bentonite Design

The lengths of the bentonite-based seals are more than 4 m, and exceed an empirical guideline for a minimum length of 2 m for clay seals (National Coal Board, 1982). The shape of the seals is expected to be cylindrical, with a diameter determined by the removal of fractured host rock. The bentonite will be mixed in approximately equal proportions with a filler material to increase its strength and limit losses through cracks or fractures. The filler could resemble Pfeifle's (1987) silica sand used as a filler with bentonite. A permeability of 10^{-19} m^2 was shown to dramatically reduce the flow through a model seal system in the Rustler (Stormont and Arguello, in preparation), and should be achievable for such a mixture. An in place density of about 1.8 g/cc for a 50/50 mixture should result in a swelling pressure of less than 3 MPa, limiting the potential for damage to the confinement (rock or concrete) and the bentonite's propensity to migrate from the seal interval through fractures in the rock or along the rock/concrete interface. The water content should be on the order of 10 percent, to reduce the likelihood of piping failure and to limit drying shrinkage.

7.2.2 Concrete Design

Two obvious design considerations are the shape and length of concrete seals. As shown in Figure 7.2, there are many possible shapes for concrete seals in the Rustler, from simple cylindrical or parallel shapes to multiple element, truncated-cone shapes. For strength considerations, the parallel shape is generally considered adequate (National Coal Board, 1982; Auld, 1983) and is the most often employed. However, Sitz (1981) argues that parallel shape will result in an unfavorable stress state upon loading sufficient to cause failure of the seal. In fact, he attributes some noteable failures to the parallel shape. Nevertheless, more recent and complete analyses have not confirmed his results (Van Sambeek, 1987).

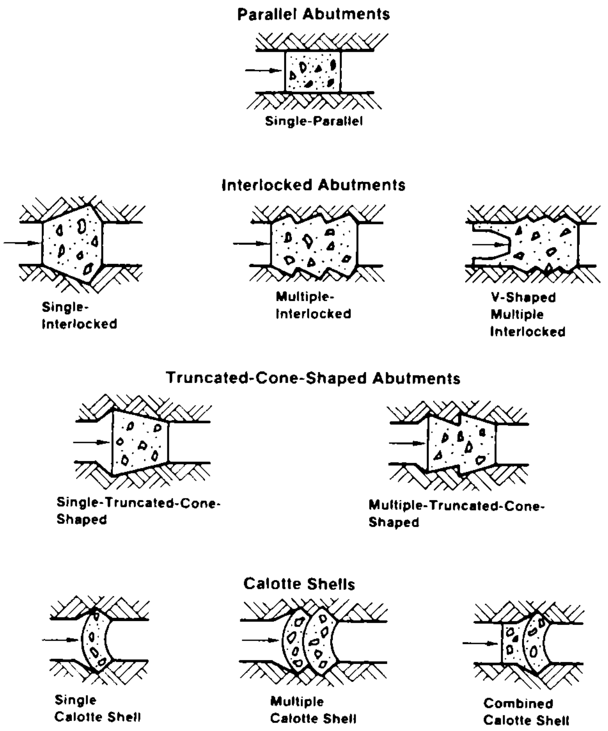

Figure 7.2. Possible Shapes for Concrete Seals (from Sitz, 1981).

Seal length can be determined by means of leakage or structural considerations. From their tests on drift seals, Garrett and Pitt (1958; 1961) regard length as governed by leakage, rather than by structural considerations. Garrett and Pitt developed concrete seal length criteria to establish the point at which leakage becomes excessive, based on allowable pressure gradient across the seal and given as a function of the contact (interface) and adjacent rock grouting associated with the concrete seal (see Table 7.1).

Garrett and Pitt stressed that these criteria are applicable only to the particular rock conditions under which the test was conducted (relatively strong and intact quartzite). They recommended that safety factors of at least four and up to ten be applied to these criteria to account for uncertainties in rock conditions and the design function of the seal. They concluded that the principal factor in a seal's performance is the condition of the host rock. This is borne out by the dramatic increase in the allowable pressure gradient across a seal when the host rock is extensively grouted. Auld (1983) recommends grouting at pressures up to one and one-quarter times the hydrostatic pressure for contact with weaker rocks. The most important point is the dramatic influence of interface contact and adjacent rock grouting on concrete seal performance.

The concrete seal has to be able to support the imposed axial load, which will be a combination of the weight of overlying seal materials and water, and possibly the load generated by expansive bentonite seals directly adjacent to the concrete seals. Simple formulae for determining the necessary length which assume a frictional contact along the interface or direct bearing on the inclined surfaces of asperities along the contact are of limited practical value, as they bear little resemblance to the actual state of stress in the concrete and adjacent rock (Sitz, 1981). Numerical studies offer the potential for a more rigorous treatment of the strength and stability of concrete shaft seals.

Van Sambeek (1987) conducted a numerical analysis of an unsupported 10 m long, 7 m diameter concrete shaft seal located at the base of the Rustler. The host rock for the seal was assumed to be sandstone, and neighboring layers of anhydrite and salt were included (Figure 7.3). The modeling of the concrete (FWC, see Chapter 6) accounted for the time-dependent elastic modulus, thermoelastic expansion, time-dependent chemically induced expansion, and creep of the concrete. The general model of the concrete behavior was based on

Table 7.1. Concrete Seal Length Criteria (from Garrett and Pitt, 1958).

	minimum p/l ratio where p is hydraulic pressure and l is seal length MPa m^{-1} (lb in^{-2} ft^{-1})
No grouting of interface or adjacent rock	0.21 (10)
Interface only grouted at hydrostatic pressure	4.72 (228)
Interface grouted at hydrostatic pressure, and adjacent rock grouted at twice hydrostatic pressure	8.28 (400)

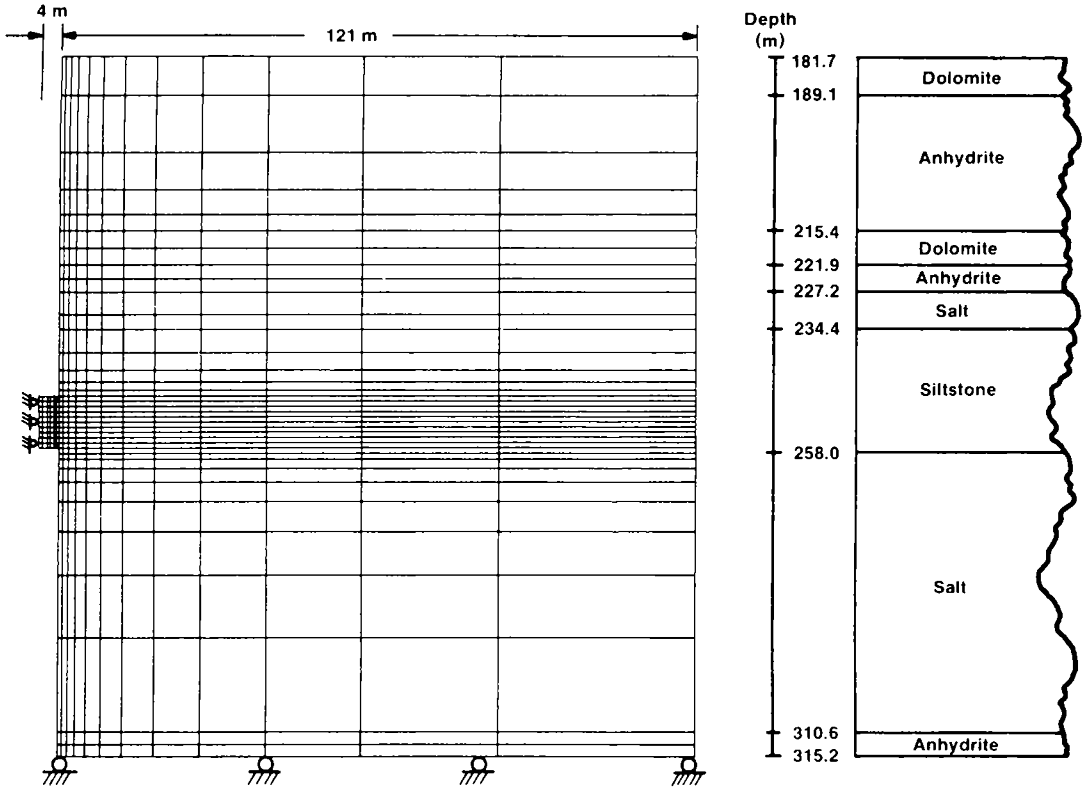

Figure 7.3. Finite Element Mesh and Stratigraphy for the Nonsalt Seal (from Van Sambeek, 1987).

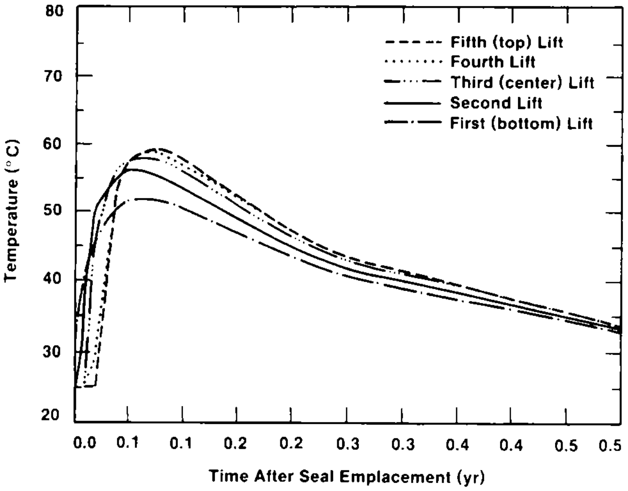

Figure 7.4. Lift Temperatures in the FWC Nonsalt Seal (from Van Sambeek, 1987).

laboratory data that had shown fair agreement with in situ test results (Van Sambeek and Stormont, 1986; Labreche and Van Sambeek, 1987). Reference properties were used for the rock (Krieg, 1984) or estimated from available literature. Thermal analyses were first used to calculate the temperature rise in the concrete and the adjacent host rock resulting from the exothermic hydration of the concrete. The peak temperature for the concrete was estimated to be about 60^{o} C (Figure 7.4), and the maximum penetration into the rock of the 3^{o} C contour was about 4 m from the seal edge. Thermomechanical analyses were then conducted to determine the state of stress and strain in the concrete and the adjacent rock from thermal expansion/contraction of the rock and concrete, chemical expansion of the concrete, and creep of the salt rock and the concrete. Radial and shear stresses at the contact and tensile stresses within the concrete were satisfactory with respect to preliminary criteria to judge the effectiveness of the concrete seal. For example, the radial stress at the interface was compressive from emplacement on, indicating a tight interface (Figure 7.5). The concrete seal was then exposed to a 10 MPa axial load (simulating the swelling pressure of an adjacent bentonite seal), and the seal remained stable. However, when the assumed expansion of the concrete was neglected, the seal was not stable, even without the axial load.

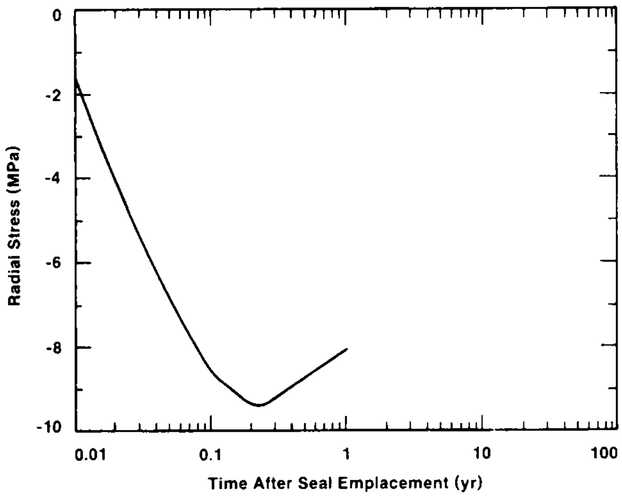

Figure 7.5. Contact Radial Stress in the FWC Nonsalt Seal (from Van Sambeek, 1987).

It is apparent from the preceding discussion that the nature and condition of the contact between a concrete seal and the host rock is an important factor in the strength and stability of a concrete seal in rock. If a good contact is provided (that is, if a substantial normal stress exists across the interface), then substantial strength in response to axial loads will be developed. This conclusion has been substantiated by laboratory push-out tests on borehole seals in rock (Stormont, 1983) and in intermediate, in situ seal tests (Stormont, 1987; Labreche and Van Sambeek, 1987). Further, as previously discussed, flow through concrete seal systems is reduced when a good contact has been provided. A satisfactory contact in these non-creeping host rocks could be provided by an expansive concrete, extensive interface contact grouting, or constructing the seal in some favorable shape.

The condition of the adjacent rock is another significant consideration in the performance of concrete seals. In addition to the influence of the adjacent rock as a significant flow path which can bypass the concrete seal, the strength of the seal system may be developed by direct bearing on the inclined surfaces of asperities along the contact. Thus, the strength of the host rock may be a factor in the stability of a concrete seal. Keying or recessing the concrete seals into the rock may provide a better seal by removing heavily damaged (fractured) rock, to provide a stronger bearing surface if required, or even to create a more favorable seal geometry if desired. Limitations of such secondary excavation are given in the next section.

In summary, the first choice for the shape of the concrete seal remains a cylindrical or parallel seal shape. The shapes of concrete seals shown in Figure 7.2 are conceptual, to indicate that the shape may be something other than cylindrical, if necessary. The lengths of the concrete seals (>10 m) are well within Garrett and Pitt's criterion with a safety factor of 10, and should be adequate if the concrete is expansive or the interface is grouted. Creating bearing surfaces by secondary excavation is a further option.

7.2.3 Sealing the Rustler Rock

Water seepage into the WIPP shafts in the Rustler has been observed to a varying degree essentially from construction on (US DOE, 1986). The upper range of these rates tends to be between 1000 and 2000 m^3/year (US DOE, 1986; Haug et al., 1986). It has been estimated that these observed inflow rates would have to be reduced by a factor of up to 1000 to limit the saturation of crushed salt seals in the Salado so as to not impede consolidation (Nowak and Stormont, 1987). If a substantial portion of the observed inflow is through the damaged zone of the adjacent rock, effective sealing will require limiting flow through this damaged zone. In other words, no matter how well the penetration or shaft opening itself may be sealed, the potential for flow in the adjacent rock must still be addressed to limit flow to the top of the Salado. This conclusion is consistent with the shaft seal model study of Stormont and Arguello (1987), as well as with case studies of effective sealing (e.g., Garrett and Pitt, 1958).

Today's approach for reducing fluid seepage from the water-bearing strata into the shafts through the existing liners has been the application of cement and chemical grouting. However, there may be difficulties and limitations for grouting applications with present technology in support of the eventual sealing of the WIPP shafts. Validated techniques for remote identification of fractures and positive confirmation of grouting effectiveness do not presently exist. Experience, notably at the WIPP, has shown that grouting often has to be repeated to obtain or maintain effectiveness. Finally, grouting may have to be effective for up to 100 years, well beyond the currently designed longevity for typical materials and applications.

Alternatives for the sealing of this region of rock include large cut-outs and overpressure systems. A sufficiently large cut-out would remove the damaged rock, and replace it with a material such as concrete. This concept has several difficulties, including determination of the distance into the rock such a structure should extend, the actual construction if the damaged zone is large, and assuring that the excavation for the cut-out does not just extend the damaged zone farther into the rock. An overpressure system involves placement of a fluid in the shaft that is at a greater pressure than the water; flow is then from the shaft out into the rock, rather than the other way. These systems, employing viscous asphalt in the annular space between the rock and liner, have been used with success in German salt mines. Limitations of this method for long-term sealing applications include assuring that the overpressure is maintained and that an adequate supply of the sealing fluid is available, as it will flow out into the rock.

7.3 Shaft Seals in the Salado

The design concepts for sealing the Salado are given in Figure 7.6. Most of the shaft will be filled with crushed salt consistent with the long-term shaft sealing strategy of maximizing the amount of consolidated salt between the repository and the top of the Salado. Other seal materials are concrete and bentonite/salt mixtures. At the top of the Salado, salt/bentonite fill is to be placed as a flow barrier and to saturate water moving down the shaft with salt. Salt/bentonite mixtures are also to be placed against the few layers which are predominantly anhydrite and thicker than 3 m because these intervals will not close from creep and crushed salt would not consolidate in these intervals (if axial consolidation is ignored). Salt/bentonite mixtures will act as a redundant flow barrier, and will perhaps seal the fractures which may result along the contact between halite and anhydrite, where large differential strains are expected. Salt/bentonite mixtures could also be placed to limit downward drainage of water added to the large volumes of crushed salt if necessary. While salt/bentonite mixtures are expected to be an excellent shaft fill material, their applications are limited to select locations because consolidated salt will be an even better long-term seal and to preclude a substantial continuous phase other than monolithic

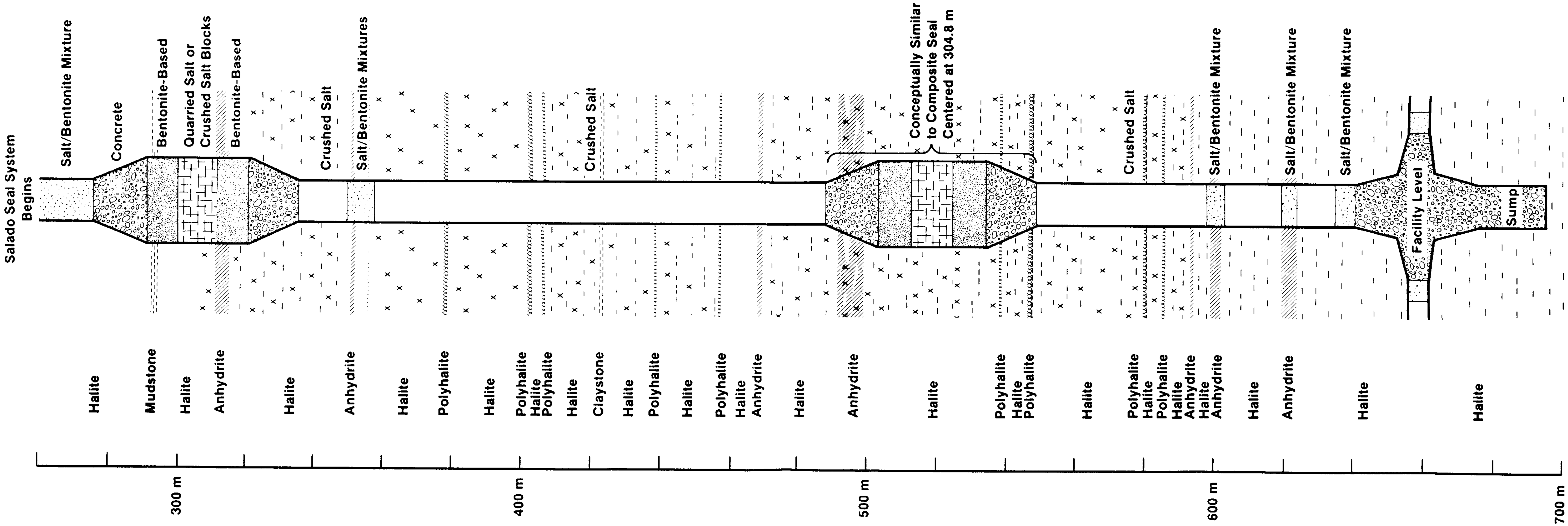

Figure 7.6. Design Concepts for Sealing the Salado.

salt in the shaft. There are two bulkhead-type or composite seals located within the Salado. The first is located nominally 15 m into the Salado, and it is the Salado counterpart to the seals in the Rustler; that is, its principal function is to limit the flow of water down the shaft from the overlying water-bearing zones. The composite seal consists of concrete, bentonite/salt mixtures, and a salt component. The salt component may be quarried or intact machined salt to hasten its return to a state comparable to intact salt. A similar composite seal is located approximately 150 m above the repository horizon. This seal separates the crushed salt that is estimated to consolidate in 100 years or less (and is therefore independent of breach scenarios) from the overlying crushed salt, which will require longer periods of time. This depth is based on a study of salt consolidation discussed in Section 7.3.1. A seal structure is located at the base of the shaft to preclude substantial settlement or movement of the overlying backfill. In addition to concrete, the base seal will have other components to restrict flow either up the shaft or down into the repository horizon.

7.3.1 Salt Seals

Scoping model calculations of crushed salt consolidation in the WIPP shafts conducted by Nowak and Stormont (1987) utilize the working criterion for salt consolidation given in Section 5.3. The model couples simplified and idealized representations of shaft closure, salt consolidation, brine influx from the host rock, and inflow from the overlying water-bearing zones. The model predicts the porosity decrease of the crushed salt due to closure concurrent with the filling of the porosity from brine influx and inflow down the shafts. As a worst case, consolidation was assumed to cease when the salt became saturated. This assumption was made to allow simple, conservative calculations. In fact, it is expected that the greater rate of closure at depth may force fluid upward, so water saturation will not necessarily preclude consolidation. Future experimental studies will address this issue. Effective consolidation was assumed to be achieved when the porosity of the crushed salt decreased to 5 percent or less. The model provides conservative estimates of the final condition of crushed salt (saturated porosity) and the corresponding time needed to achieve its final condition as a function of depth. The representations of closure, brine influx, inflow from the overlying water-bearing zones, initial porosity of the crushed salt, and time of emplacement after excavation were varied in order to assess the sensitivity of the model to these parameters. Over and above revealing the sensitivity of the model to parameters such as closure and brine influx, conclusions regarding the shaft seal design were reached. First, a preliminary criterion for the allowable or target flow from the overlying water-bearing zones was developed. Figure 7.7 reveals the influence of inflow down the shafts on the length of the effectively consolidated salt column at the bottom of the shaft. Baseline values representing best estimates were selected for the other parameters. If the flow is limited to 1 m^3/year or less, at least 100 m of salt will reach 5 percent or less porosity within 100 years. Another conclusion from this study is that the initial density of the crushed salt in the shafts should be as great as practicable to minimize the time to consolidation. In fact, the 100 m of consolidated salt in 100 years requires an initial density achievable only by salt blocks. It should be emphasized that the model is believed to be conservative; that is, the actual amount of consolidation is expected to be greater than the model predicts. However, it provides quantitative results that can be used to provide guidance for the experimental program, as well as design-relevant information.

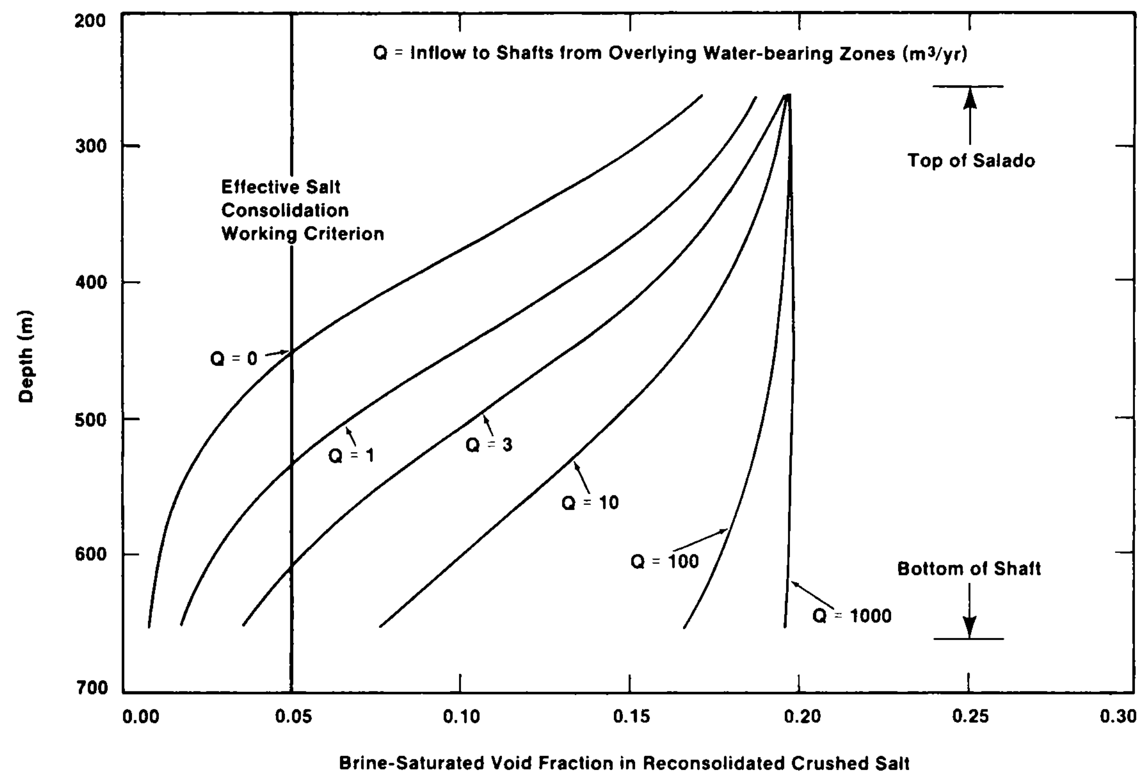

Figure 7.7. Sensitivity of Salt Consolidation in the WIPP Shafts to Brine Inflow from Overlying Water-Bearing Zones (from Nowak and Stormont, 1987).

There are presently no estimates of the time required for quarried salt to achieve its final condition, but it is assumed to be less than that for crushed salt blocks.

7.3.2 Bentonite Design

The bentonite mixtures in the Salado could contain salt or sand as the filler material. A 50/50 mixture of bentonite and a filler with an in place density of about 1.8 g/cc will result in a low permeability seal which generates moderate swelling pressures. The minimum seal length should be 4 m. Emplacement of bentonite mixtures in block form offers good control over the in place properties. The discussion regarding shape and length of bentonite-based seals from Section 7.2.1 applies to the bentonite component in the composite seal. For the bentonite mixtures at the top of the Salado and against anhydrite layers, confinement by crushed salt blocks rather than concrete is specified. The pores in the crushed salt blocks have been sufficiently small to prevent substantial loss of bentonite in intermediate size tests in the WIPP (Stormont and Howard, 1987).

7.3.3 Concrete Design

Results from the Small-Scale Seal Performance Tests have been very favorable with regard to the establishment of tight, stable concrete seals in salt. Test Series A involved the placement of six concrete seals in vertically-down boreholes, and thereby simulated shaft seals in halite host rock (Stormont, 1986). Three different sizes were emplaced: 15.2 cm dia, 30.4 cm length; 40 cm dia, 61 cm length; 91 cm dia, 91 cm length. The concrete was the ESC mixture. Measurements of strains and stresses in the concrete seals and the adjacent rock revealed that the strains and stresses are compressive in nature, and are tending toward equilibrium. Creep of the adjacent host rock was identified as the predominant mechanism for the development of stresses and strains in the concrete (Stormont, 1987). The stability of the seal system was not threatened by permeability measurements, which imparted a 2 MPa axial gas pressure on one face of the seals, implying that the concrete/rock interface has substantial strength. Fluid flow measurements indicate that the seals are excellent barriers to fluid flow (Peterson, Lagus, and Lie, 1987b). Both brine and gas flow tests determined that five of the six seals had permeabilities of less than 10^{-18} m^2. There was no breakthrough of brine during a 140-day test at 3.5 MPa driving pressure on the 60 cm long seal (Peterson, Lagus, and Lie, 1987b).

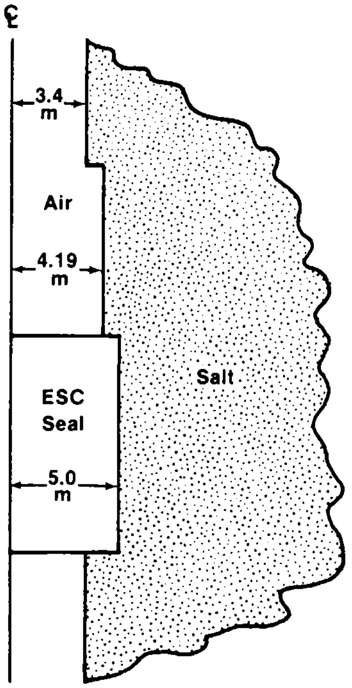

Figure 7.8. Configuration of Modeled Concrete Seal in Top of Salado (from Van Sambeek, 1987).

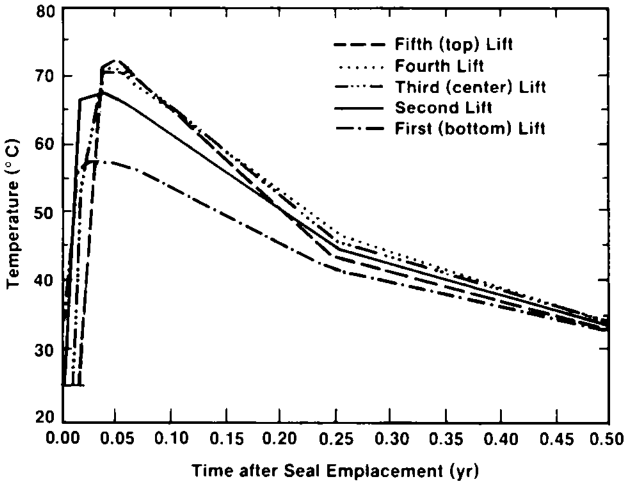

Figure 7.9. Lift Temperatures in the ESC Salt Seal (from Van Sambeek, 1987).

As part of the numerical analyses of shaft seals described in Section 7.2.2., Van Sambeek (1987) evaluated a 10 m long, 7 m diameter concrete shaft seal located in the top of the Salado. The seal was slightly recessed into the formation to account for the removal of the shaft key and any remnants of the chemical seal material that had been behind the key (Figure 7.8). The concrete was modeled as the ESC, using the best available representations of the concrete properties. The temperature rise in the concrete was 72°C (Figure 7.9), and the maximum penetration of the 3°C temperature rise contour was about 5 m from the seal edge. The subsequent thermomechanical modeling of the seal system accounted for the time-dependent properties of the salt, as well as those of the concrete. The model results imply that the seal system is structurally stable. Consider the modeled radial stress at the rock/concrete interface given in Figure 7.10. The stress buildup within the first 0.2 year is a result of the

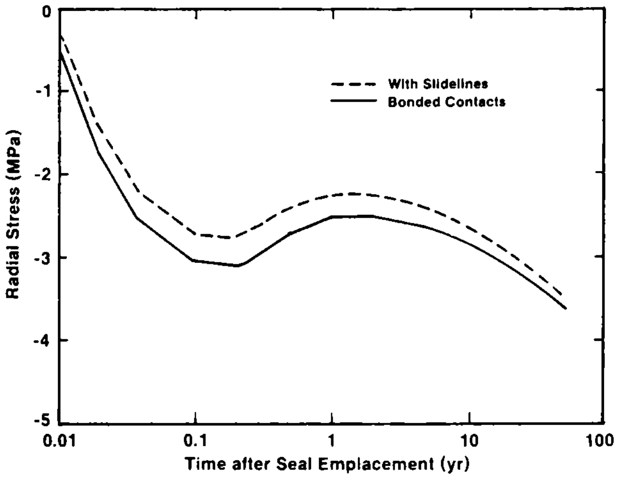

Figure 7.10. Contact Radial Stress in the ESC Salt Seal (from Van Sambeek, 1987).

chemical expansion of the concrete and thermal stresses resulting from the heat liberated during hydration. The subsequent decrease in radial stress is due to the cooling of the concrete and the salt. The stress increase after about one year is a result of creep of the host rock; eventually, the radial stress would approach the lithostatic value of 6 MPa. Axial loads of 10 MPa to simulate the swelling of adjacent bentonite-based seals produced tensile stresses in the concrete that were largely attributed to the artificial modulus of the salt (one-twelfth of the measured value) used to improve creep closure calculations (Van Sambeek, 1987). Due to the dominant effects of salt creep, when the concrete was modeled without expansion the stresses in the seal system tended toward the same values as with expansion.

Both the in situ tests and the numerical study indicate that the biggest advantage of concrete seals in salt is the tendency of the rock to creep in on the seal to effect a tight, stable interface that results in an early, positive seal without waiting for extensive salt creep. The shape previously given in Figure 7.6 is conceptual, to indicate that a shape other than a simple cylinder may be required. The length of approximately 10 m should be adequate.

7.3.4 Sealing the Salado Rock

Placing seals in halite will in time reduce permeability in the surrounding formation and the interface. When a relatively stiff inclusion (such as concrete immediately after emplacement and crushed salt after it appreciably consolidates) is located in an opening in rock salt, the tendency of the rock to creep will cause the radial and tangential stresses in the vicinity of the inclusion to approach the lithostatic stress. These stresses are expected to reverse the disturbance (including a decrease of permeability) in the adjacent rock by literally forcing the rock back together. Further, the stresses at the seal/rock interface are expected to become great enough to render the often-troublesome interface tight. Thus, emplacing certain seals may not only seal the excavation, but may also return the adjacent rock to a near pre-excavation condition.

"Disturbance reversal" as described above has been observed in laboratory testing of halite, and has been referred to as "healing." When samples of salt are brought from the field (in a disturbed condition), their permeabilities are usually great. After application of hydrostatic pressure, permeabilities decrease to a low value and remain fairly insensitive to stress changes (Sutherland and Cave, 1979). Healing is generally attributed to decreased porosity from plastic deformation at the grain boundaries. Another type of healing that may occur in halite is macroscopic fracture healing. Limited tests of fracture toughness suggest that fractures in halite heal appreciably when subjected to moderate pressure and temperatures (Costin and Wawersik, 1980). IT Corporation (1987) found that confining pressure and elevated temperatures reduced the permeability of fractures in salt with time to a level comparable to that prior to fracturing.

Healing has also been observed in in situ tests. Test Series B of the Small-Scale Seal Performance Tests involved 1-m-long horizontal concrete seals emplaced in 1-m-diameter boreholes (Stormont and Howard, 1986). Approximately 30 days after seal emplacement, tracer gas and flow measurements indicated that while the volumetric flow rates were quite small, very fast travel times (<10 minutes) through the seals were measured. In one case, the flow path was identified as a fracture either along the interface or in the adjacent rock; in the other two cases, the flow paths were assumed to be along cabling routes within the seal. Follow-up measurements approximately one year after seal emplacement revealed that the flow paths previously observed had shut down--no tracer made it through any of the seals even after being introduced behind the seals at 2 MPa for 12 days (Peterson, Lagus, and Lie, 1987b). Pressure measurements within the concrete seals indicate the development of relatively high radial stresses near the interface over the course of the year (Labreche and Van Sambeek, 1987), consistent with the concept of concrete/rock healing.

Grouting of the Salado is possible, but is neither desirable nor thought necessary as a primary seal. Effective grouting may be difficult due to the small size of the fractures and the tendency for movement of the host rock. At present, the best design option is to utilize the potential of the rock to heal itself under certain conditions.

7.4 Design Options Including Asphalt

Asphalt could be used as a component in the shaft seals if the redundancy that it can provide was thought necessary. Asphalt must be suitably confined to prevent its loss through cracks or fractures; therefore, the adjacent host rock must be without substantial fractures. A material should be placed above and below the asphalt that does not allow the asphalt to travel along its interface with the host rock. Sitz (1981) demonstrated the ability of clay/sand mixtures to retain asphalt. Sitz also determined that the asphalt layer should be more than 1.5 m thick to achieve a good seal.

The designs given in Figures 7.1 and 7.6 could be modified by specifying a layer of asphalt in the middle of the bentonite-based seals. It may be difficult to locate a sufficiently unfractured section of host rock in the Rustler without displacing the position of the bentonite-based seals. In the Salado, there is ample space. Also, the creep of the adjacent rock salt may produce a natural overpressure system with the viscous asphalt, increasing its sealing ability.

8. DESIGN EVALUATION OF PANEL SEALS

Due to its predicted rapid consolidation, quarried or crushed salt is the principal seal material for storage panel seals. Special care, or actions such as overexcavation, will be necessary to address the disturbed rock zone problem.

8.1 Panel Sealing Strategy

The strategy for panel sealing is to prevent the seal location from providing a preferential flow path out of the storage panel. In this way, pressurized fluid within a storage room (if there were any) would be equally likely to move out through the host rock as it would through the sealed drift and shaft, greatly decreasing the amount of fluid that might reach the biosphere if the sealed penetrations were the predominant flow path. Such a strategy again suggests emplacing a seal that becomes virtually identical with the host rock (that is, a salt-based seal). As will be shown, effective salt seals are expected to be established well within 100 years, consequently their development will not be impeded by human intrusion. The effect of brine influx from the host salt into the consolidating salt is expected to be of less concern than in the shafts. Loading of the panel seals by waste-generated gas has not been explicitly considered in design activities. The seals as presently designed will allow gases to pass through them fairly easily until they consolidate, at which time the seal will be essentially identical to the host rock. Further, as waste will be emplaced on either side of most panel seals, the loading will be nearly symmetric and will not tend to displace the seals. Gas generation, dissipation, and pressure buildup must be evaluated in the context of the entire storage system, not just the panel seals. Once a satisfactory model of gas generation exists, the room response, including panel seals, can be evaluated.

The condition of the host rock is a critical consideration in the strategy, design, and performance of panel seals. As previously discussed, the flow through a seal system is partially dependent on host rock permeability. This becomes even more important for panel seals because the seal axis is aligned with that of the formation bedding and discontinuities, increasing the opportunities for seal bypass. Furthermore, the rectangular shape of the excavations at the facility horizon is expected to result in more disturbance than a circular or elliptical shape. The panel seal designs will have to take the adjacent disturbed rock zone into account.

The current sealing concept calls for panel seals in main access drifts and in the panel entries (Figure 8.1). These seals will isolate the disposal area from the shafts, and the panels of waste from one another. The WIPP

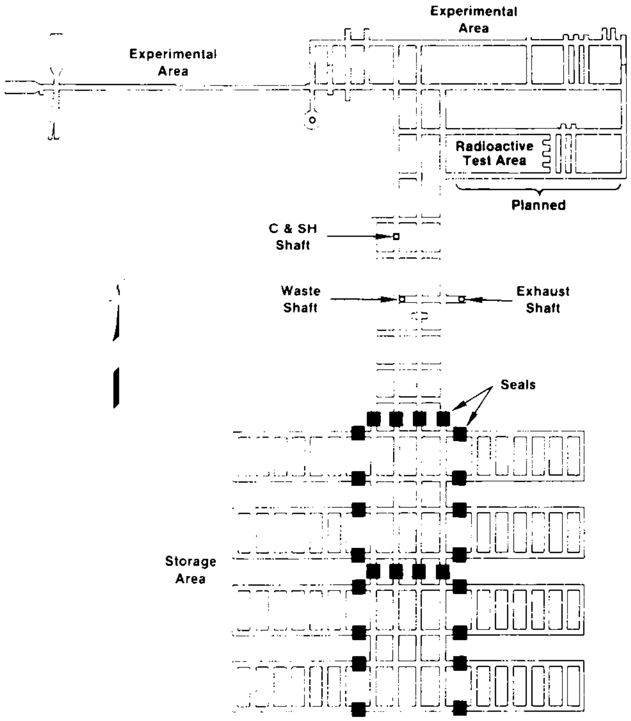

Figure 8.1. Tentative Locations of Panel Seals.

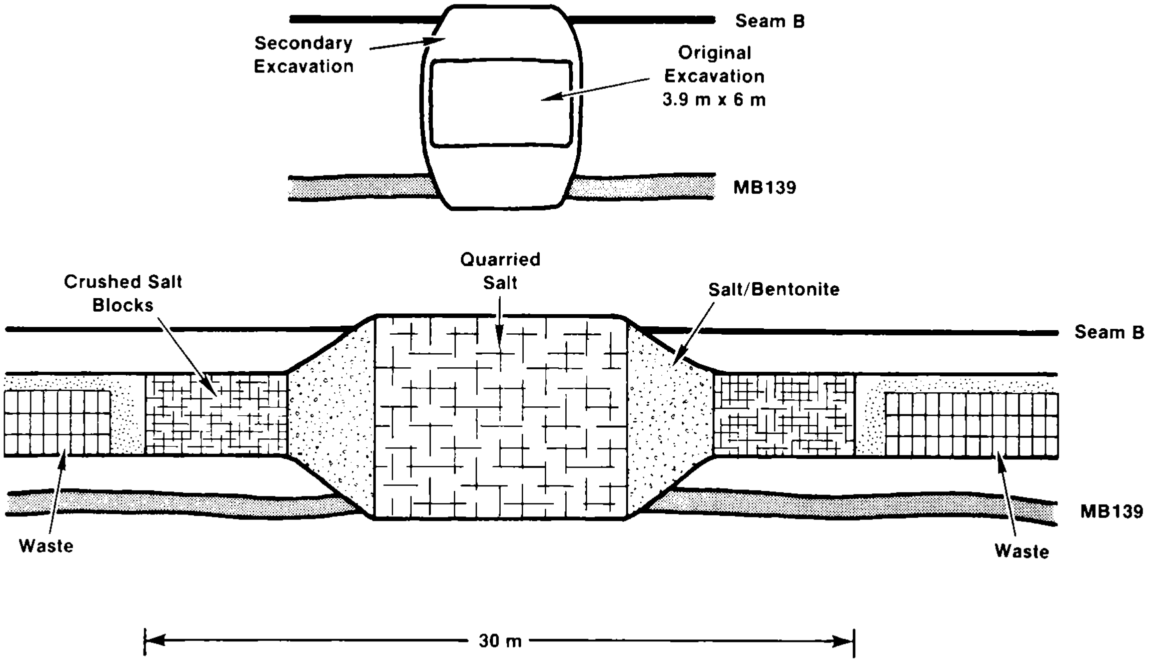

Figure 8.2. Cross-Sectional View of Panel Seals.

Facility design calls for reduced width in the 60 m long panel entries (from 3.9 m high by 9.9 m wide in the storage area to 3.9 m high by 4.0 m wide in one entry and 3.9 m high by 6.0 m wide in the other), and for 30 m of the entry dedicated for a panel seal (US DOE, 1986). Panel seal designs will be developed within the 30 m length constraint if possible. The dimensions of the main access drifts are 3.9 m high by 4.0 m wide, and the remaining one is 3.9 m high by 7.5 m wide.

8.2 Panel Seal Design

The panel seal design is given in Figure 8.2. A center or core of quarried or crushed salt is the principal long-term seal component. At this location, the design calls for the rock to be overexcavated just prior to seal emplacement to remove damaged rock. Salt/bentonite mixtures in block form or pneumatically emplaced will be located on either side of the core principally as a short-term seal component. Pressed salt blocks are the exterior components to confine the bentonite and to serve as a redundant long-term seal. The shapes and sizes of the seal components and the overexcavation in Figure 8.2 are conceptual.

8.2.1 Salt Seal Design

Test Series C of the Small-Scale Seal Performance Tests is providing data on the structural and fluid flow performance of block-type seals that simulate panel seal components (Stormont and Howard, 1987). Eight seals, 92 cm wide, 92 cm high, and 92 cm long, were emplaced in boreholes drilled in the rib (wall) of the WIPP Facility. Four seals are composed of salt blocks, and four seals are composed principally of salt/bentonite blocks. There are four seals instrumented with pressure and closure (displacement) gauges: two salt block seals and two salt/bentonite block seals. The remaining four uninstrumented seals (two salt and two salt/bentonite) are for permeability or fluid flow testing. In order to install the block-type seals in cylindrical horizontal boreholes, the seal intervals were "squared" into rectangular parallelepipeds and therefore have a shape similar to a drift. Methods of block production and seal emplacement devised suggest that block-type seals are viable full-size seal structures. Structural measurements include hole closure in open and sealed portions of the boreholes, pressure changes at the seal/rock interface, and axial displacements of the seals. These measurements provide data to test laboratory-based models of salt consolidation. To date, the measurements are consistent with the conclusion of Sjaardema and Krieg (1987) that crushed salt seals should provide little resistance to hole closure until they become very dense.

The consolidation of a crushed salt panel seal has been modeled by Arguello and Torres (1987). A two-dimensional plane strain geomechanical model of the panel entryway and seal component was used to numerically simulate the seal system response. The drift was modeled as 3.7 m wide by 6.1 m high, and the seal was assumed to be infinitely long in the out-of-plane direction. Reference stratigraphy and material properties were used for the formation, with the exception of an artificial reduction in the elastic modulus for the rock salt to better simulate measured closures. The crushed salt was assumed to provide no backstress to closure up to a fractional density of 0.95 (Sjaardema and Krieg, 1987); therefore, the crushed salt seal was indirectly modeled as an open drift. The study parametrically varied the initial density of the crushed salt and the time of seal emplacement after excavation. Results showing the change in fractional density with time, for various initial fractional densities and for times of emplacement after excavation of 0.5 and 10 years, are given in Figures 8.3 and 8.4, respectively. Clearly, the time required to reach 0.95 fractional density (the working criterion of effective salt consolidation as discussed in Chapter 5) decreases with increasing initial fractional density. Further, for the same initial density, the time to reach 0.95 fractional density is increased the longer after drift excavation that the seals are emplaced. A conclusion from this study is that for an opening 10 years old or less, an initial fractional density of 0.8 or greater is required to achieve the working criterion of 0.95 fractional density in less than 100 years, and will therefore be established prior to any breach scenarios. Such a fractional

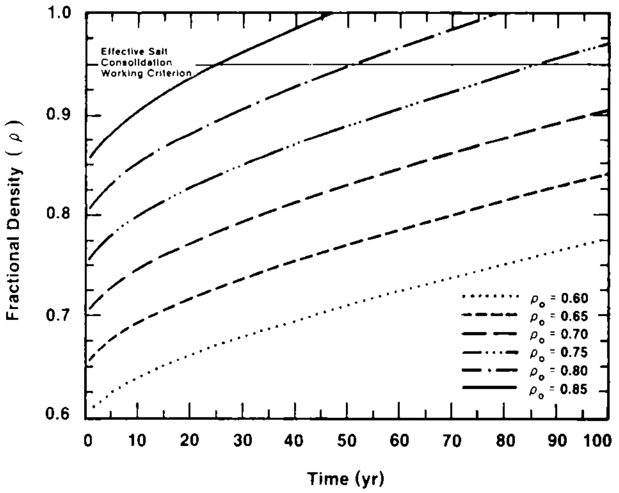

Figure 8.3. Fractional Density with Time for Seal Emplaced at 0.5 Years After Excavation (from Arguello and Torres, 1987).

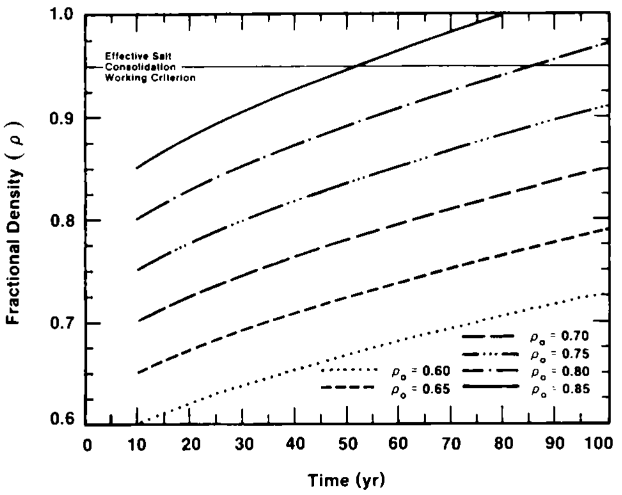

Figure 8.4. Fractional Density with Time for Seal Emplaced at 10 Years (from Arguello and Torres, 1987).

density is achievable by pressed blocks (Stormont and Howard, 1987).

Once its fractional density exceeds 0.95, crushed salt will develop a stiffness approaching that of intact salt. Therefore, stress build-up and the accompanying disturbance reversal is expected in the rock adjacent to a relatively dense crushed salt seal.

Extrapolation from the shaft salt consolidation study by Nowak and Stormont (1987) reveals that the expected rates of brine influx will not saturate a mass of crushed salt at the repository horizon until its fractional density is well above 0.95. Therefore, brine influx should not prevent salt from consolidating adequately as a panel seal component.

An effective seal should be achieved faster with quarried salt. Quarried salt would also limit disturbance in the adjacent rock, as it would take less closure to effect a seal, and it becomes stiffer faster, resulting in a stress buildup in the vicinity of the seal.

8.2.2 Salt-Bentonite Seal Design

A salt/bentonite seal component would add a short-term flow barrier function to the panel seal. Such a seal component would remain effective even if it did not consolidate substantially as a result of the "bridging" of closure from the relatively stiff adjacent quarried salt block component. The bentonite would be confined by the pressed or quarried salt blocks on either side of it. The bentonite may seal fractures in the anhydrite or salt rock if they are not too large.

Initial fluid flow testing of the salt/bentonite seals in Test Series C suggested that the salt/bentonite blocks can be effective barriers to brine flow if interface erosion is prevented. Salt blocks provided adequate confinement for the salt/bentonite blocks under these test conditions (Stormont and Howard, 1987).

8.2.3 Rock Sealing

The formation could provide a path for fluid to bypass the panel seals. The inherent low permeability of far-field or intact salt will probably preclude unacceptable bypass, but the disturbed zone may be troublesome. In a bedded deposit, especially when the predominant rock (salt) continues to deform in a nearly stable stress-field, separations or fractures associated with the interbed layers are to be expected. The relatively thin layer of salt on the roof and invert between the excavation and the interbed layers may also fracture. The fractures could become a network of connected porosity throughout the storage facility. The fractures may be confined to immediately above and below the excavation, or may extend some distance. Such fractures could ultimately connect waste disposal areas with other portions of the facility.

The most direct method of detecting and measuring disturbance surrounding WIPP Facility excavations has been gas flow or gas permeability tests (Stormont, Peterson, and Lagus, 1987). Results of these gas flow tests in test intervals composed of rock salt are given as a function of distance of the test interval from the excavation in Figure 8.5. Beyond 1 m the flow rates are consistently small, and within 1 m of the excavation flow rates vary by many orders of magnitude. When the test interval containing an interbed layer was distant from the excavation, the measured flow rates were low; relatively high flow rates occur when the interbed is within about 2 m of the excavation and the measurement has been made near the center of a drift or intersection (Figure 8.6). As shown in Figure 8.7, the wider the drift, the more flow is measured in the interbed when measured from the center of the drift.

Tests conducted in the first panel entries provide a good illustration of the dependence of disturbance on time and size. Gas flow measurements conducted in the rock immediately above and below these drifts began about 1 month after excavation and were periodically repeated. The following conclusions are drawn from these measurements: (1) at all times, the flow rates in the wider (6.0 m) drift are substantially greater than in the narrower (3.9 m) drift; (2) the flow rates in the wider drift increase more dramatically with time (Borns and Stormont, 1987). Contours of gas flow rates measured around a 5 year old WIPP drift similar in size to a panel entry are given in Figure 8.8 (Borns and Stormont, 1987). Tracer measurements imply that vertical and horizontal flow paths (both microscopic and macroscopic fractures) exist above and below the excavations, and are located in Marker Bed 139 below, Seam B above, and the salt that separates these layers from the excavation (Stormont, Peterson, and Lagus, 1987).

Visual observations of fractures in boreholes in the rock surrounding excavations have also provided direct information regarding the disturbed rock zone. The observations are summarized in Figure 8.9's idealized cross-section of a storage room (Borns and Stormont, 1987). Reexamination of existing boreholes by Franke (1987) suggests a very strong dependence of fracture frequency on drift span and time after excavation.

Continuing deformation is likely to result in increased flow or permeability in the rock adjacent to seal locations, so it appears prudent to install seals to limit the deformation as soon as possible after excavating and filling the rooms with waste. It may be feasible to install some of the panel entry seals within a few years after excavation, but the main access ways may be open for 30 years prior to decommissioning. A different seal design may be required in locations that have been open for long periods of time.

A fundamental issue is whether to overexcavate the rock at the panel seal locations. Some overexcavation is presently believed necessary because disturbance (i.e., fractures) is expected to develop quickly after excavation and get progressively worse, and it seems unlikely that healing can reverse all of this disturbance within 100 years. Within one year after excavation, the anhydrite layer beneath the floor of the first panel entry way had fractured extensively (Borns and Stormont, 1987). While healing of halite in the vicinity of panel seals may reverse some disturbance once the seal components densify sufficiently to exert appreciable backstress, fractures in anhydrite are not expected to readily heal, and even if they are forced back together it is likely that the surfaces will not match perfectly and the fracture will remain open. Overexcavation may allow the drift to possess a more favorable geometry that will minimize post-sealing

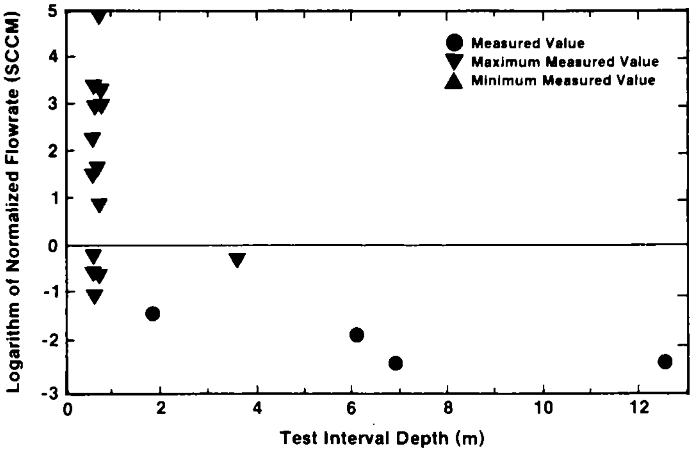

Figure 8.5. Gas Flow Rates in Halite Test Intervals. (from Stormont, Peterson and Lagus, 1987).

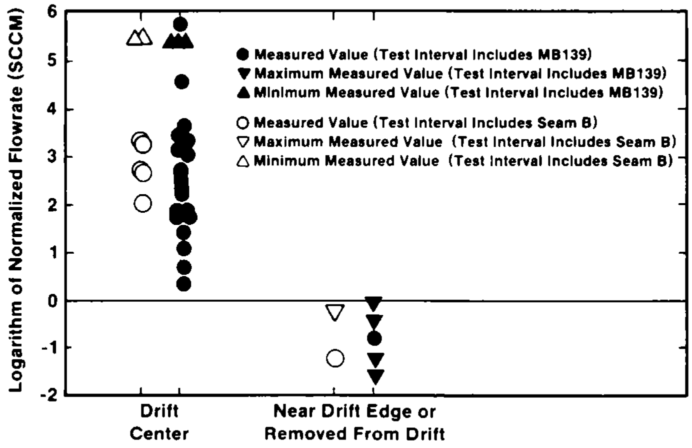

Figure 8.6. Flow Rates in Interbed Layers Within 2 m of WIPP Drifts When Tested at the Drift Center or Near or Just Removed from the Drift Edge (from Stormont, Peterson, and Lagus, 1987).

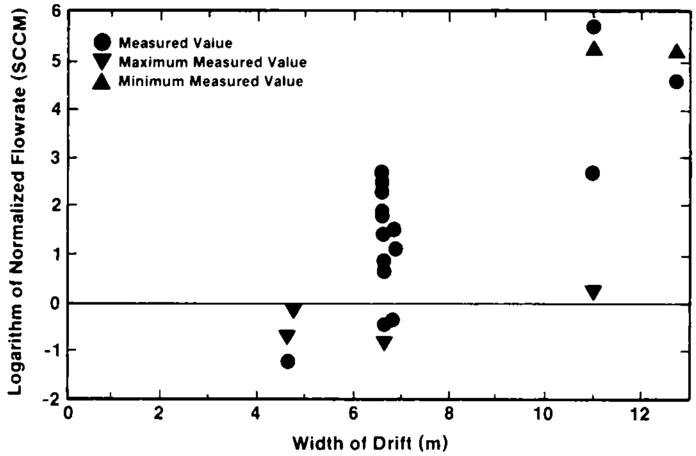

Figure 8.7. Drift-Width vs. Flow Rate From Tests on MB139 (from Stormont, Peterson, and Lagus, 1987).

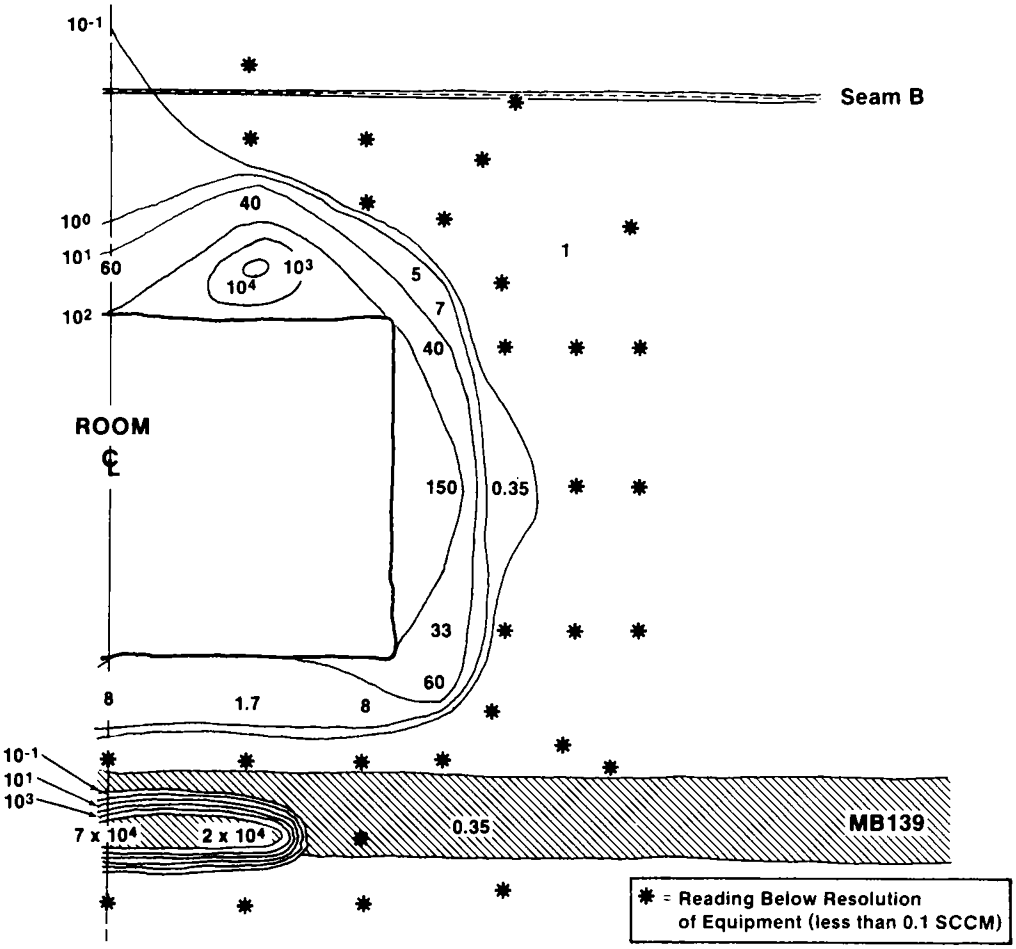

Figure 8.8. N1100 Drift Flow Rate (SCCM) Contours (from Borns and Stormont, 1987).

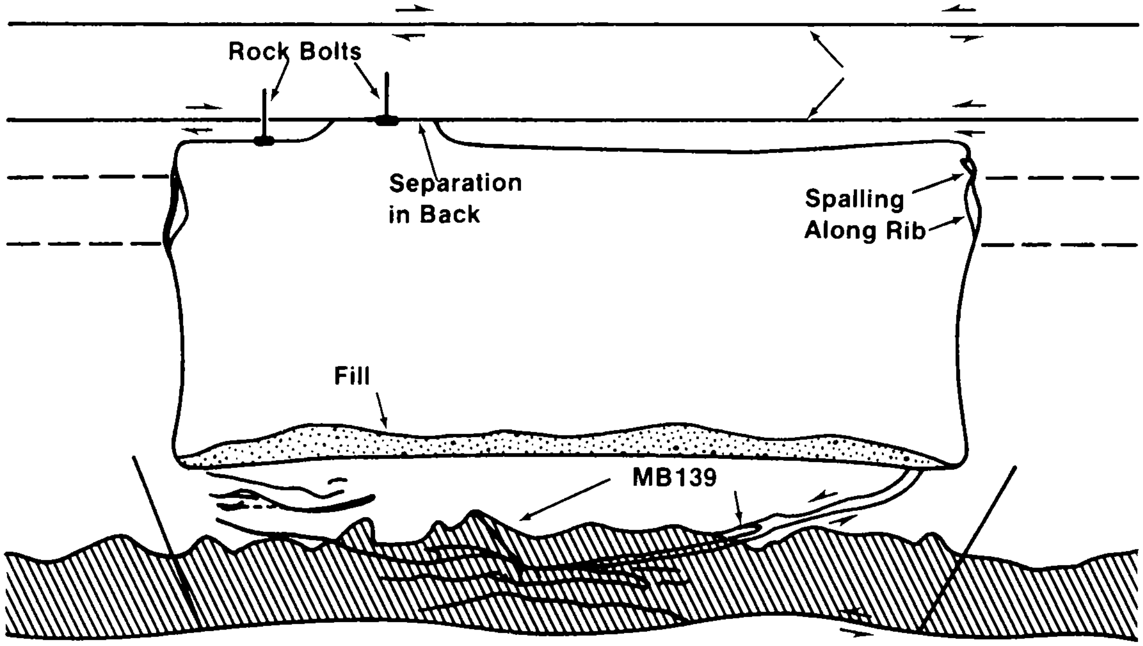

Figure 8.9. Idealized Excavation Effects in a 4m x 10m Room from (Borns and Stormont, 1987).

damage. However, the limitations of overexcavation should be recognized: it will entail additional costs, there is no experience with or data from the overexcavated drift configuration, and as the effective diameter of the opening increases, the disturbed zone may propagate further into the rock.

The overexcavation should be done just prior to seal emplacement if possible, to minimize disturbance and utilize the increased creep rates of the host salt just after excavation. It is likely that portions of Marker Bed 139 and Seam B will have to be removed. The most favorable shape may be elliptical, rather than rectangular. Limited grouting of Marker Bed 139 in the vicinity of the overexcavation may be required to fill large voids.

8.3 Design Options Including Concrete

Many alternative designs for panel seals can be generated by including concrete as a component. Concrete components are presently not thought necessary to establish effective panel seals, but they are retained as a secondary design option. Concrete could be used for many reasons: (1) if salt consolidation assumptions are not substantiated; (2) for confinement of salt or bentonite-based seal components; (3) to reverse formation disturbance; (4) as a short-term flow barrier; (5) as a redundant component. Due to the length of time that they will be open, the seals in the main entries may require concrete components. The shaft base seal (introduced in Chapter 7) is likely to include concrete.

Test Series B of the Small-Scale Seal Performance Tests involved three 92 cm diameter, 92 cm long concrete (ESC) seals emplaced horizontally in the rib of Room M (Stormont and Howard, 1986). These seals simulate panel seals in an idealized (circular) geometry. Two seals contain thermal/structural instrumentation, and one is uninstrumented. The concrete was pumped into place, and the resulting seals had an excellent contact with the host rock. Structural results indicate that the seals are stable, even when axially loaded to 2 MPa during flow testing (Labreche and Van Sambeek, 1987). Trends indicate that axial stresses may become tensile about two years after emplacement, perhaps eventually resulting in fracture. As with Test Series A, the creep of adjacent rock was the predominant mechanism of stress and strain development in the concrete and the adjacent rock after transient effects diminished. The results of fluid flow tests of these seals indicated that they were excellent barriers to fluid flow and become more effective with time, due to the healing effect (Peterson, Lagus, and Lie, 1987b) discussed in Section 7.3.4.

Arguello and Torres (1987) conducted analyses of concrete panel seal components. The model was identical to that previously used for their analyses of the crushed salt component (Section 8.2.1), except the crushed salt was replaced with a concrete seal. The concrete was modeled as linearly elastic, and the material constants were those for the ESC (Gulick and Wakeley, 1987). The analyses were carried out to 50 years, where the seal system response is assumed to be dominated by salt creep. Previous modeling by Van Sambeek (1987) and Van Sambeek and Stormont (1987) suggests that the effects of hydration and expansion diminish with time for a concrete seal in salt because of the dominant long-term effect of salt creep. When the concrete was loaded by the creep of the adjacent rock, the calculations predicted that essentially no tensile stresses developed in the concrete, and the compressive stresses were well below the strength of the concrete. Tensile stresses which exist in the rock prior to seal emplacement (which indicate potential locations for fractures) were predicted to disappear and become compressive soon after seal emplacement; within five years after seal emplacement no tensile stresses exist. Thus, a concrete component is expected to generate a stress field in the adjacent rock that is conducive to healing or tightening of the halite host rock. Results from Test Series B that substantiate this prediction are discussed in Section 7.3.4.

A composite panel seal consisting of a central crushed salt core with concrete end caps was analyzed by Arguello (1988). A two-dimensional, axisymmetric geomechanical model was used to estimate the effect of a finite length composite seal and the influence of the stiff concrete end caps on the consolidation of the central core (bridging). The concrete seals were 5.4 m in diameter and 5.3 m long, and the salt core was 5.4 m in diameter and 19.8 m long. The composite seal was assumed to be emplaced two years after excavation. Fractional densities of the crushed salt core as a function of time after emplacement are given in Figure 8.10 for an initial salt fractional density of 0.8. The effect of the concrete is largely confined to within 2 m of the concrete/crushed salt transition. Data from Test Series B imply that the closure of a borehole is largely unaffected by a concrete seal within one-half

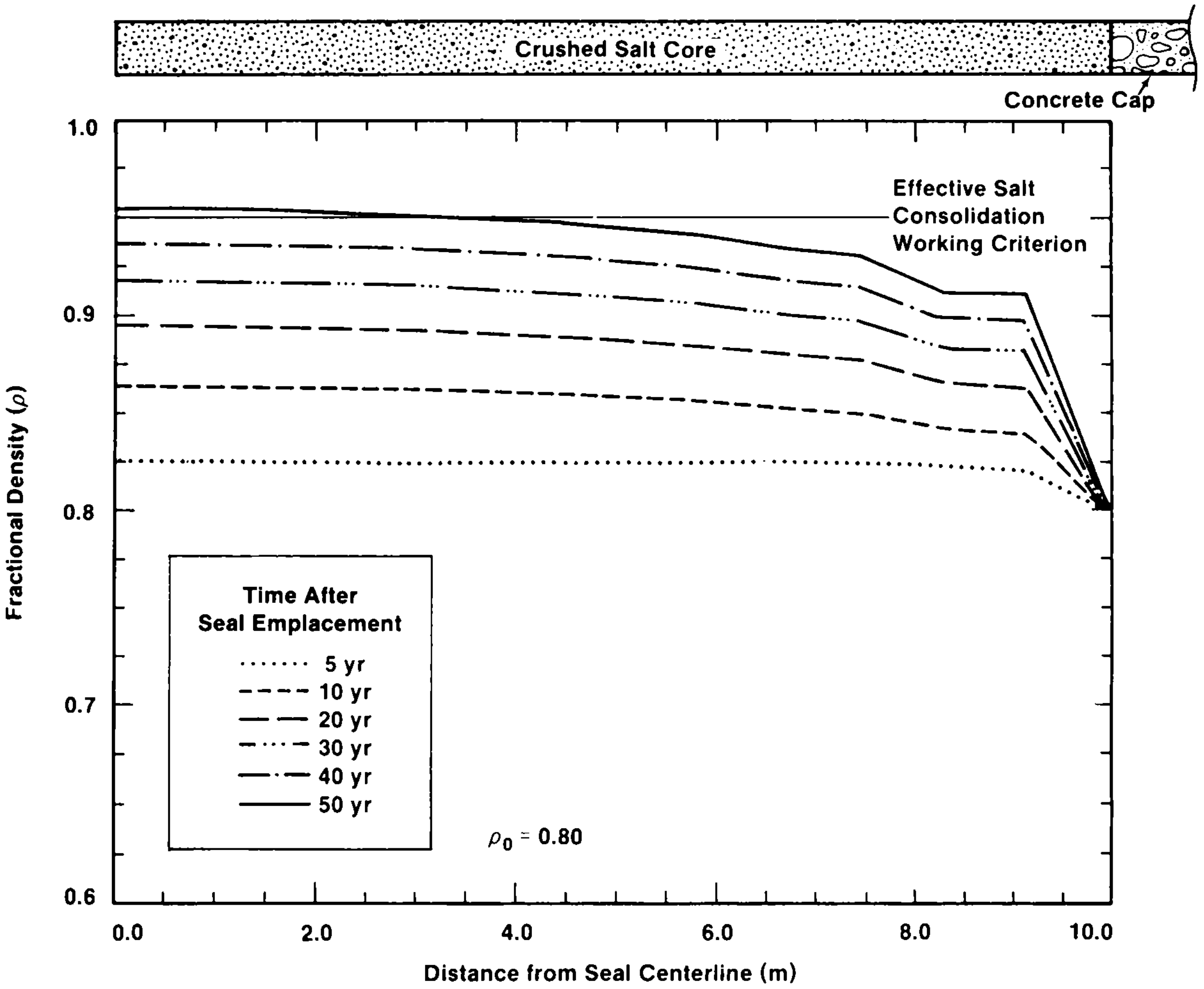

Figure 8.10. Fractional Densities of the Crushed Salt Core as a Function of Time After Emplacement (from Arguello, 1988).

of a hole diameter away from the concrete face (Labreche and Van Sambeek, 1987), and are therefore consistent with this modeling study. Arguello also predicted that unacceptably high axial tensile stresses develop in the concrete soon after seal emplacement, and suggested that reinforcement or seal geometries other than simple cylindrical ones may be necessary. Test Series B data indicate that tensile strains develop in the concrete, but there is uncertainty over the stress measurements (Labreche and Van Sambeek, 1987).

9. DESIGN EVALUATION OF NON-WASTE ROOM SEALS

The non-waste rooms are to be sealed by backfilling with crushed salt.

9.1 Non-Waste Room Sealing Strategy

Non-waste rooms or drifts are all excavations not presently dedicated to eventual waste disposal, including the experimental areas. It is presently planned to seal non-waste rooms by backfilling with crushed salt. The purpose of backfilling these areas is to provide a redundant barrier to fluid migration, limit the damage around these excavation, shorten the time until the repository is returned to a condition comparable to intact rock, and serve as a disposal location for mined salt.

9.2 Non-Waste Room Seal Design

The non-waste rooms should simply be backfilled with crushed salt. No secondary excavation is anticipated. Pneumatic stowing or backfilling may be the emplacement method of choice because: (1) relatively high initial densities can be achieved; (2) there is good control over the consistency of the emplacement; (3) it is relatively inexpensive; (4) emplacement can be achieved remotely to avoid regions of possible danger.

The time to achieve effective consolidation can be inferred from analyses for consolidation of panel seal components (e.g., Arguello, 1988; Arguello and Torres, 1987). Based on these analyses, consolidation should be complete in less than 200 years. Because of the time the excavations will be open prior to sealing and the lack of preparation or treatment of the adjacent disturbed zone, substantial additional time may be required to reverse the adjacent formation damage.

10. DESIGN EVALUATION OF BOREHOLE SEALS

Cementitious grouts will be used to seal boreholes in the vicinity of the WIPP, probably without removing the hole casing. Present analyses suggest that crushed salt may not be effective for borehole sealing.

10.1 Borehole Sealing Strategy

Previous assessments have indicated that open existing boreholes in the vicinity of the WIPP pose little or no threat to the public (Intera, 1981; Christensen, Gulick, and Lambert, 1981; Stormont, 1984), principally because no existing boreholes penetrate the WIPP Facility and salt must be dissolved in the boreholes before penetration could occur. Such dissolution is calculated to proceed slowly, and the requirements for borehole sealing are therefore expected to be minimal. Because concerns regarding long-term performance are alleviated for borehole seals, cementitious mixtures can be used as the principal seal material.

Cement-based materials (grouts) are preferred as borehole seal material for their emplacement characteristics. Borehole sealing entails remote emplacement, and confidence is required that the sealing material completely fills the borehole and makes good contact with the borehole wall. This may be particularly important in boreholes penetrating rock susceptible to substantial washouts (Christensen, Statler, and Peterson, 1980). Cement grouts have known flow properties and established emplacement techniques that allow good rock/seal contact. Even if the grout degrades into its constituents (principally sand), adequate resistance to flow should exist (Stormont, 1984).

10.2 Borehole Seal Design

The saltwater BCT-1F mix (Section 6.3.1) should be placed in the salt zones to preclude dissolution of the host rock by the cement water. On the other hand, the freshwater BCT-1FF mix is preferred in nonsalt zones because of its slightly better performance characteristics.

A fundamental issue concerning borehole sealing is whether or not the casing should be removed prior to sealing. Iron casing will corrode over long periods of time, leaving a more permeable conduit through the seal (Tremper, 1966; Tonini and Dean, 1976). However, because all boreholes which penetrate the Salado are unlined below the Rustler contact with the exception of ERDA-9, a seal of substantial length which has a good bond with the host rock will be emplaced even if the hole is left cased. Very short borehole seals emplaced in salt in Test Series A of the Small-Scale Seal Performance Tests have exhibited permeabilities to gas and brine of less than 10^{-18} m^2 (Peterson, Lagus, and Lie, 1987b). The Bell Canyon Test demonstrated the effectiveness of short grout borehole seals in anhydrite host rock (Christensen and Peterson, 1981). Given the probable minimum sealing requirements for boreholes, it is believed that adequate seals can be achieved with the casing left in place above the Salado.

10.3 Design Options Including Crushed Salt

While it would be desirable to achieve a salt seal in boreholes, present concerns regarding emplacement techniques and brine saturation prior to achieving high fractional densities do not make it a first choice material for borehole seals. Bridging of a granular material during remote emplacement in a relatively small diameter is possible. Concerns over bridging and the complete filling of the borehole can be partially alleviated by first screening the salt to eliminate large grains, perhaps to a distribution similar to sand, and then emplacing it through tubing that is withdrawn during filling. Screening may also help to obtain the highest possible initial density of the crushed salt.

Even if the crushed salt could be emplaced effectively, the consolidation may be impeded by saturation of the crushed salt by brine from the host rock salt. Salt consolidation calculations for shafts (Torres, 1987) can be related to salt consolidation in a borehole by applying the "pseudostrain concept" (Munson, Torres, and Jones, 1987), which in essence states that closure in homogeneous salt is directly proportional to its diameter. The fractional density of a crushed salt seal with time is therefore independent of the opening diameter, as long as the initial fractional density is the same. Thus, the results of Torres (1987) showing the change in fractional density with time for an initial fractional density of 0.60 (see Figure 10.1) apply to salt consolidation in boreholes, as well as in shafts. The present best estimates of brine influx, however, predict that once short-lived transients diminish, the volumetric flow rate is independent of excavation diameter, or stated differently, that the flux is

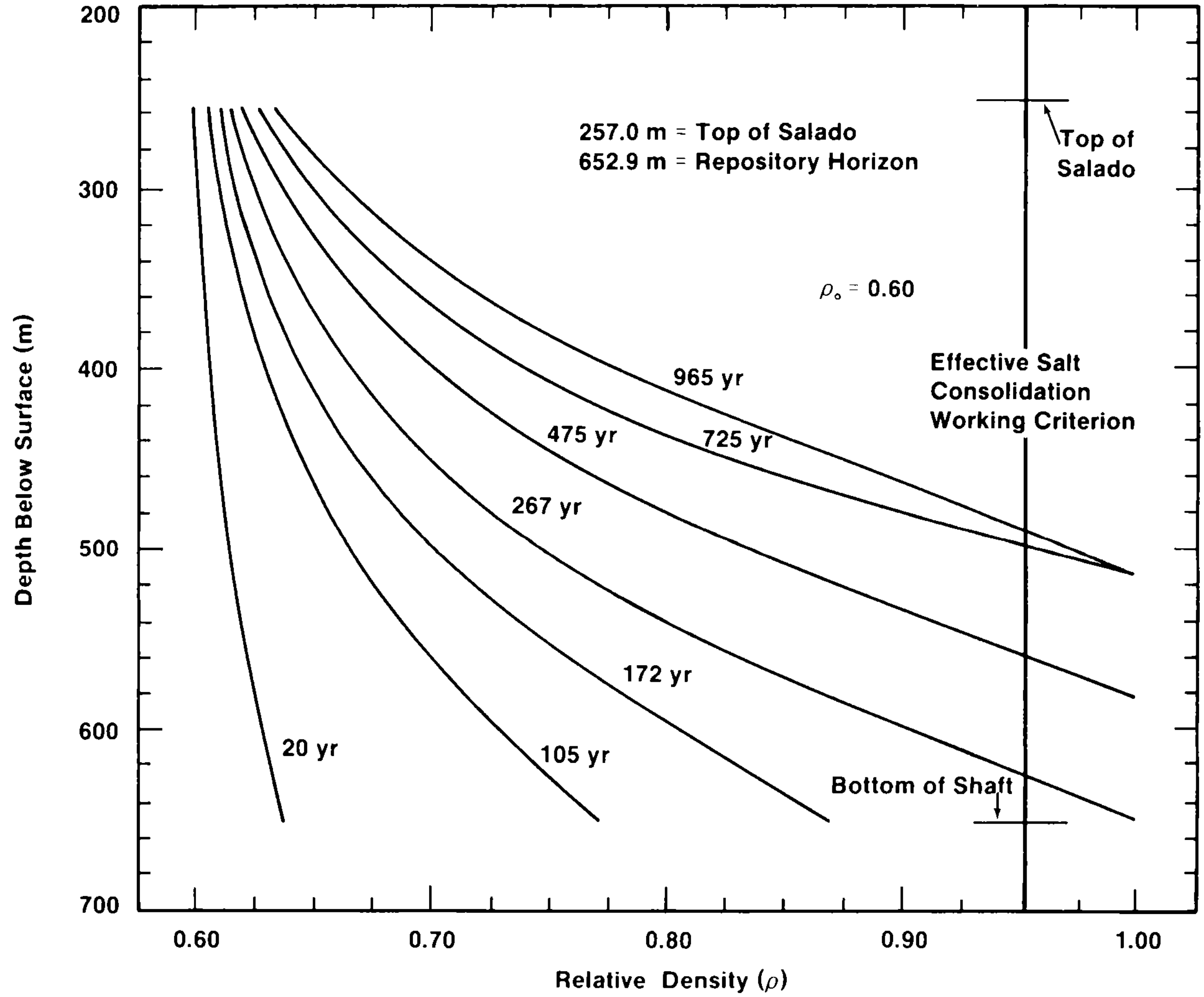

Figure 10.1. Backfill Density for a 3.66-m-Diameter Shaft (initial density = 0.60; from Torres, 1987).

inversely proportional to the opening diameter (Nowak and McTigue, 1987). Therefore, for the expected rates of consolidation and brine influx in boreholes, the crushed salt will become saturated prior to consolidating appreciably and the working criterion of Chapter 5 is not satisfied.

11. CONCLUSIONS

Salt consolidation is the key element of the design concepts for sealing the WIPP. To date, all indications are that the behavior of crushed salt is amenable to constructing long-term seals. There are many options for emplacement, and all of them are available, practical and not excessively costly. The recently developed and demonstrated block technology is a significant advancement in emplacement of crushed salt. Small amounts of moisture have consistently and dramatically increased consolidation rates in laboratory tests. In addition, permeabilities were shown to drop markedly at a fractional density of 0.95. The constitutive relationship for crushed salt based on the laboratory tests reveals that the salt will provide little resistance to closure until fractional densities exceed 0.95, at which point they have become effective barriers to flow. A working criterion developed for satisfactory consolidation was a fractional density of 0.95 or greater prior to saturation. Model studies of salt consolidation in shafts show that under conservative assumptions a >100 m long seal of consolidated salt at the base of the shafts can be expected if excessive water from the overlying water-bearing zones is ruled out. Finite element modeling of salt consolidation in panel seal components shows that effective salt consolidation is expected in less than 100 years at these locations. An alternative for emplacing salt seals is the use of quarried salt blocks. This technique, while not yet as advanced as crushed salt consolidation, could substantially reduce the time required to achieve an effective, long-term salt seal should that be desirable.

The design evaluation reveals that the host rock is expected to significantly influence the adequacy of seal systems. The adjacent rock can be the predominant flow path through a seal system, as demonstrated by model studies and in situ test results. In the shafts, rock in the Rustler Formation may be of particular concern due to its diversity and relative inaccessibility. At the disposal horizon, the anhydrite/clay interbed has been observed to contribute substantially to a disturbed rock zone. In halite, the tendency for the host rock to creep has positive benefits. First, the closure consolidates the seal material. Once the seal material resists continued closure, the rock stresses increase and tend to tighten the seal/host rock interface. This effect, known as healing or disturbance reversal, has been simulated numerically and observed during in situ tests.

Bentonite-based seals have many favorable properties, including low permeability and moderate swelling potential. Model results suggest bentonite's importance in effecting adequate shaft seals in the Rustler. Bentonite can be tailor-mixed with other materials, such as sand or crushed salt, and emplaced in many different ways, including blocks. Initial results from in situ tests are favorable for bentonite/salt mixtures as barriers to fluid flow. Bentonite-based materials are being used in other experimental programs throughout the world, and the data base is therefore growing rapidly. The long-term physical and chemical stability of bentonite in WIPP environments is promising, but largely unsubstantiated.

Cementitious materials have been developed for placement in different WIPP environments (salt and nonsalt) with adequate material properties and emplacement characteristics. These materials have been emplaced and tested in situ in numerous configurations, and have demonstrated exceptional sealing ability. Structural and thermal measurements have been used to improve numerical models of concrete/salt interaction. Numerical simulations of concrete seals in shafts and panel seal locations have indicated that stable seals should be achievable, but indications of tensile stresses in concrete seals emplaced in halite have been noted.

There is presently no known fundamental obstacle to effectively sealing the WIPP by implementing the design concepts contained herein. Therefore, the present long-term sealing considerations support waste isolation at the WIPP. The designs, however, are not complete. Much work will be required to confirm these design concepts prior to the WIPP conversion from a pilot plant to a repository in about 1992. Key elements of the ongoing experimental program are given below.

11.1 Materials Development

Laboratory testing of salt consolidation and permeability will continue, with emphasis on developing a mechanistic model of consolidation. The recently developed constitutive model will be tested against new laboratory data, and applied to potential seal configurations.

The quarried salt concept will be evaluated to determine its feasibility. Emplacement technology, laboratory testing, and model simulations will be developed if warranted.

The long-term physical and chemical stability of bentonite-based seal materials will be investigated.

Basic properties and efficacy of asphalt seals will be obtained from existing literature.

Continued testing of laboratory samples of cementitious material will continue, with emphasis on indications of long-term stability. Grout development for formation grouting in the shafts will be pursued if necessary.

11.2 Formation Hydraulic Properties

Measurements of permeability, pore pressure, and brine influx will be made in the soon-to-be-excavated Air Intake Shaft.

Measurements to characterize the time-dependent development of the disturbed rock zone surrounding excavations at the facility horizon are being conducted. These measurements include gas permeability and dye injection tests.

Further tests to determine brine influx size effects and the pressure regime in the vicinity of the WIPP Facility are being implemented. A drift-scale test is planned.

11.3 Seal Tests

The Small-Scale Seal Performance Tests have provided a wealth of practical information and data in return for a modest investment. The existing test series will be maintained to provide data on time-dependent effects, and future test series are being designed and implemented to simulate shaft seal components.

A full-size test of a seal component will be required to provide reasonable assurance that the concepts developed on a relatively small-scale can be extrapolated to their intended application. Present plans are for a test of crushed salt block and quarried salt seals to be installed in conjunction with a drift-size brine influx experiment.

11.4 Seal Design and Modeling

The models of crushed salt consolidation in the Salado portion of the shafts and the flow through the seals in the Rustler portion of the shafts are being coupled to provide a more realistic model for the progressive consolidation and saturation of the crushed salt column in the shafts.

Various loading conditions and geometries will be investigated to develop a stable concrete seal design for salt and non-salt host rocks. The necessity of concrete expansivity will be investigated.

11.5 System Integration

An adequate and defensible design will require the integration of laboratory data, in situ data, and modeling results. Results from other experimental programs must also be considered, including performance assessment activities. A system analysis approach for the entire seal system and its subsystems will be implemented to ensure that the design is adequate.

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