ONWI-405

Schematic Designs for Penetration Seals for a Reference Repository in Bedded Salt

Technical Report

November 1982

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DISCLAIMER

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ABSTRACT

The isolation of radioactive wastes in geologic repositories requires that man-made penetrations such as shafts, tunnels, or boreholes are adequately sealed. This report describes schematic seal designs for a repository in bedded salt referenced to the stratigraphy of southeastern New Mexico. The designs are presented for extensive peer review and will be updated as site-specific conceptual designs when a site for a repository in salt has been selected.

The principal material used in the seal system is crushed salt obtained from excavating the repository. It is anticipated that crushed salt will consolidate as the repository rooms creep close to the degree that mechanical and hydrologic properties will eventually match those of undisturbed, intact salt. For southeastern New Mexico salt, analyses indicate that this process will require approximately 1000 years for a seal located at the base of one of the repository shafts (where there is little increase in temperature due to waste emplacement) and approximately 400 years for a seal located in an access tunnel within the repository. Bulkheads composed of concrete or salt bricks are also included in the seal system as components which will have low permeability during the period required for salt consolidation.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

D'Appolonia Consulting Engineers, Inc. (D'Appolonia) is contracted with the Office of Nuclear Waste Isolation (ONWI) to develop designs for penetration seals at candidate National Waste Terminal Storage (NWTS) sites. This report describes schematic designs for penetration seals for a repository in bedded salt. The designs are referenced to the stratigraphy and hydrology of the Permian salt deposits in southeastern New Mexico. To a large extent, the designs should be readily adaptable to any bedded salt site, and perhaps to a dome salt site, although in all cases it will be necessary to take into account site-specific characteristics.

1.1 OBJECTIVES AND SCOPE

The general objective of the repository sealing program is to develop licensable, cost-effective designs for penetration seals and storage room backfills for candidate NWTS repositories. Penetrations which are being considered include shafts and tunnels used to gain access to the repository, storage rooms and connecting tunnels within the repository, boreholes drilled from the surface (whether pre-existing or drilled for repository site characterization), and boreholes drilled from within the repository for exploration. Backfill that may be placed in waste-canister emplacement holes is not considered part of the sealing system, although it is recognized that there may be considerable coupling between emplacement hole and storage room backfills.

The research and design efforts and programs necessary to develop reliable, credible procedures for repository sealing follow two parallel but interconnected paths:

1. Site-specific designs developed for candidate repositories. The sites included initially will be Hanford (basalt), Nevada Test Site (tuff) and an ONWI site in bedded or dome salt. Designs for a repository in granite may be completed at a later date.

2. General scientific and technical studies applicable to sealing at all or most sites (e.g., materials testing, development of criteria).

This report presents site-specific schematic designs for penetration seals at a repository in bedded salt. Schematic designs are considered to be working designs, presented for extensive peer review, which will be updated as new data, information, and requirements become available. Schematic designs serve a number of functions:

- To summarize progress in design development and illustrate design concepts.
- To aid in developing media- and site-specific design considerations.
- To assist in pointing out data deficiencies and research needs.

The schematic designs presented in this report are referenced to the NWTSR-2 conceptual design for a repository in bedded salt and to the stratigraphy and hydrology of the WIPP site. The WIPP site has been used as the reference geology only to take advantage of the comprehensive geologic data base available from site characterization for WIPP. The WIPP site is not a candidate site for a repository for commercial wastes, and the NWTSR-2 repository design is not being used for the WIPP repository.

1.2 DESIGN SCHEDULE

The schematic designs presented in this report will be modified as schematic designs for a candidate commercial waste repository in salt when a specific site has been selected and preliminary site characteristics are available. The updated designs may incorporate additional data available from ongoing or planned laboratory or field testing (Figure 1-1), but will not differ greatly in scope or detail from the designs presented herein. Ongoing or planned laboratory and field test programs include materials testing at Pennsylvania State University and Waterways Experiment Station, bench-scale testing of borehole plugs at Terra Tek, and hydrologic testing in boreholes by Systems, Science, and Software.

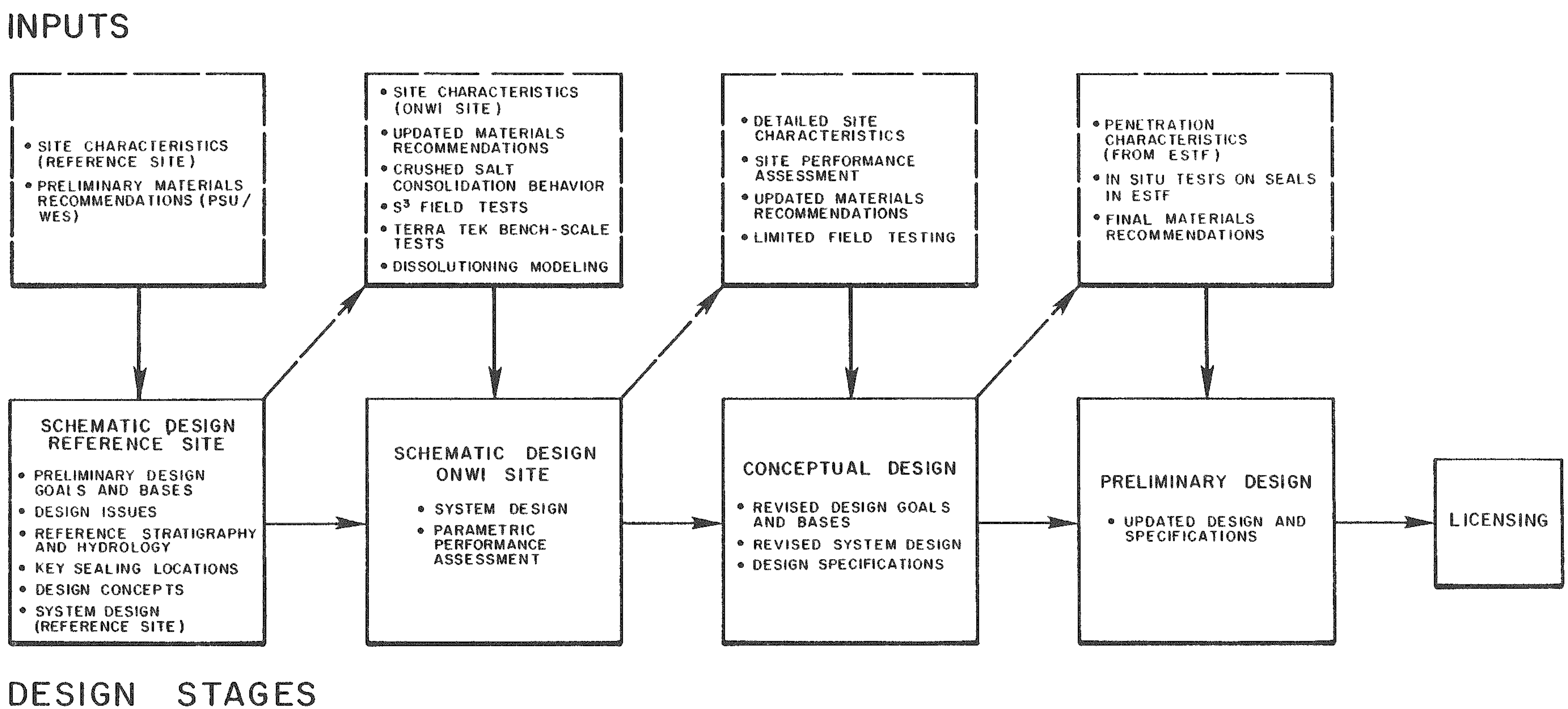

Figure 1-1. Stages in Design Development for Penetration Seals in Salt

Subsequently, schematic designs will be updated as conceptual designs and, later, as preliminary designs. Conceptual designs will be comparable in detail with the conceptual designs prepared for the repository and will specify seal component dimensions, materials properties and construction methods. Conceptual designs will be linked to quantitative design goals and bases (Section 1.4) developed by means of site and seal performance modeling. They will be considered to be complete in that they should address all known design issues, but they will be prepared prior to in situ testing in an early shaft test facility. Preliminary designs will incorporate site and penetration characteristics obtained from shafts and tunnels at the candidate repository site and will be supported by in situ testing of seals or seal components. Preliminary designs will be sufficiently complete and detailed to be submitted to the regulatory authority as part of a license application for repository construction.

1.3 DESIGN APPROACH

The overall approach for developing seal designs follows two parallel lines, both of which are iterative. The first is the development and refinement of a hierarchal system of objectives, leading from design goals to design bases, which are necessary to keep the efforts focused toward identified schedule milestones. Design goals and bases are considered further in Section 1.4. The second line is the development of design concepts that will successfully lead to detailed design specifications. The progressive design development involving schematic, conceptual, and preliminary designs in support of licensing has been noted in Section 1.2.

The design development is purposefully iterative in order to take into account peer review, performance assessment, and data from laboratory and field testing between each of the major stages. In the schematic and conceptual stages, laboratory tests are important for selecting and characterizing seal materials. Field tests assume more importance between the conceptual and preliminary stages. Analytical studies are important at all stages in the design development. In the schematic and conceptual stages, simplified analytical models are used both to determine seal performance requirements and to demonstrate the relative sensitivity of various design parameters affecting performance. In the conceptual and preliminary design stages, increasingly complex models will be used in performance assessment (comparing against results from field tests) and consequence analyses of radionuclide releases.

The designs presented in this report are developed according to an approach that is generally applicable to all candidate repository sites. Elements of the approach include:

- Designs use existing (1980's) technology.
- Design goals are developed with recognition of applicable Environmental Protection Agency (EPA) and Nuclear Regulatory Commission (NRC) standards and guidelines.
- Issues are resolved by a logical progression from office studies, to laboratory tests, and to field tests.
- A sealing "systems" approach is used considering room backfills, tunnel seals and backfills, and shaft seals as subsystems within a single system.
- Designs incorporate multiple components with each component designed for a specific function (or combination of functions), and to be compatible with a specific location and environment. Components may be distinguished by geometry, materials, or construction methods. Repetition of components provides redundancy within the overall system.
- The number of materials used is sufficient to satisfy the appropriate component functions and geochemical environments, but is limited to a reasonable range that can be verified in laboratory and field programs.
- Performance assessment models for all seal systems are based on techniques that can be verified within the licensing process.

- To the extent possible, initially specified construction techniques use existing methods, recognizing that techniques may be improved during the repository operational period.

- To the extent possible, performance assessment uses parametric analyses in order to define the sensitivity of design parameters and the types and scope of performance demonstrated tests required.

- Technical conservatism is provided by means of redundancy in the multiple-component design and the use of appropriate safety factors and design assumptions.

The design approach is both flexible and rigorous. Flexibility is required in order to accommodate progressively more detailed data from site characterization and materials testing, and to be adaptive to evolving regulatory criteria. A rigorous approach is required to ensure that the eventual licensing process leads to success. This requires not only a system design which meets or exceeds all safety requirements but also a well developed and documented rationale which can be used to convincingly defend a design against those standards.

1.4 PERFORMANCE REQUIREMENTS

1.4.1 General Approach

The design approach for penetration seals involves the development and refinement of a hierarchal system of objectives leading from design goals to design bases. Design goals are statements of the overall required performance. Design bases are the quantitative limits on performance of various aspects of a seal system, specified such that if these bases are met the design goal will be met automatically. Design bases, as the term implies, are the bases for determining design specifications which are the quantitative and detailed translation of design bases into specific aspects of seal design such as material properties, shape, number, and location of seal components, and construction methods. Design specifications are such that once they are satisfied appropriate design bases and design goals will also be satisfied. (It may be noted that the term "performance requirements" may be used generally as in this report, or more specifically to mean either design goals or design bases.)

Figure 1-2 shows two parallel pathways converging in the development of design bases for conceptual seal designs. One pathway uses detailed site performance assessment to evaluate the relative importance of penetration seals in limiting total releases to the biosphere. Concurrently, the second pathway leads to conceptual designs via schematic designs which are based on preliminary design goals and bases derived qualitatively or semi-quantitatively without the use of rigorous site and system models. As shown by Figure 1-2, there are several important interfaces between site activities (characterization and modeling) and seal design. Site characteristics are required as input to design; in return seal design indicates data required from site characterization. Also, seal performance derived by parametric modeling of schematic designs is an important input to system performance assessment.

The major objectives for site performance assessment will be to predict overall site performance with respect to a variety of release scenarios and to compare performance against the standards promulgated by the EPA. The relative influence of the sealed penetrations can be determined by means of 3 types of models:

(i) Models with no penetrations are used to determine site performance with no contribution to releases from the penetrations.

(ii) Models with open penetrations are used to determine worst case releases through the seals.

(iii) Models with sealed penetrations are used to determine the sensitivity of system performance to variations in seal performance.

In the case of a repository in salt it might be anticipated that normal releases from the site should be very small and perhaps negligible. Seal performance may then have a significant influence on overall system

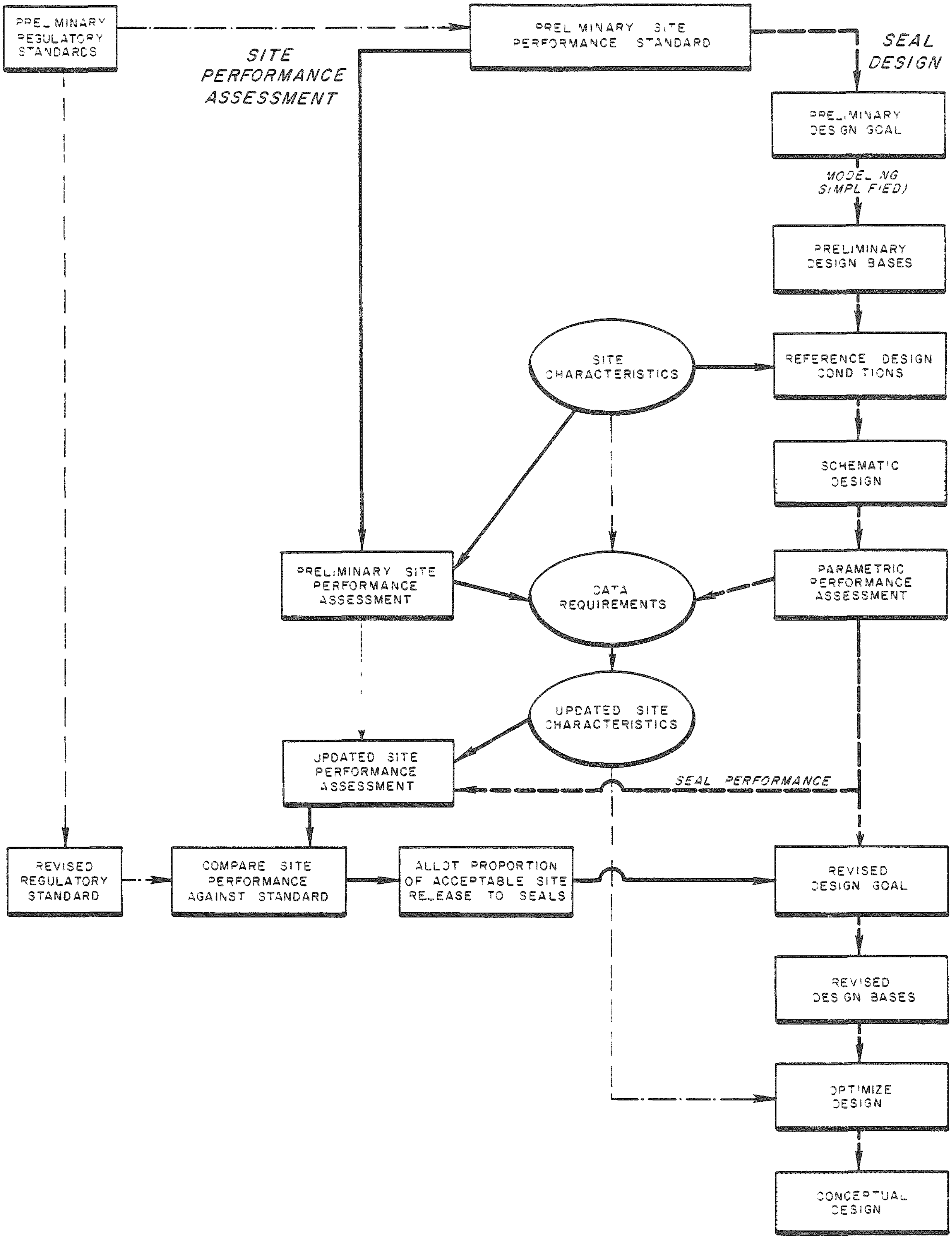

Figure 1-2. Interrelationships Between Seal Design Activities and Site Performance Assessment in Developing Performance Requirements for Seal Design

performance and emphasis should be given to the third type of model described above. Schematic seal designs required as input to this type of model are developed as shown in Figure 1-2. Qualitative and semi-quantitative approaches for developing preliminary goals and bases for schematic designs are described in the following sections.

1.4.2 Preliminary Design Goal

The overall design goal for penetration seals has been stated as follows:

> "The radionuclide migration rate through the seal zone is always less by a specified factor of safety than an acceptable level determined by a consequence analysis" (D'Appolonia, 1980a).

One way to define an "acceptable level" is to allow the seal system to contribute a proportion of the maximum allowable release from the site as a whole, as determined by the EPA. The design goal may then be restated as:

> Radionuclide release through the seal system(s) should be less than ---(a specified proportion) of the maximum release for the repository system as a whole allowable by regulatory standards.

This design goal is deliberately related to the maximum release allowable by regulatory standards rather than to the release actually predicted for the site discounting the penetrations. Any general standard which did limit seal releases to below a proportion of the predicted site release would tend to be over-restrictive for seals designed for sites with small predicted releases (such as many salt sites). As a preliminary guideline for development of schematic designs, it is suggested that the proportion of the total allowable site release allotted to the seal system should be in the range 5 to 10 percent. At present, this range is proposed as being simply an order of magnitude less than the maximum acceptable repository release. In the future it may be possible to develop a more rigorous approach for determining the maximum release that can be allotted to the seal system. It is possible that the design goal modified in the future may allow a higher proportion of the total release through the seals. This may be particularly true for a repository in salt where the predicted releases through the rock mass are likely to be small.

1.4.3 Preliminary Design Bases

Having specified a general design goal, the next stage in developing criteria is to develop quantitative design bases and design specifications. For repositories in general, rigorous design bases and specifications for penetration seals will be established ultimately by modeling. This modeling will examine credible release scenarios and driving forces, and will assess seal performance in the context of the performance of the site as a whole. Consideration will be given to extreme cases, including models in which the penetrations are unsealed and models in which the penetrations do not exist, as well as to models with various seal systems. Such modeling will establish the importance of high quality seals relative to the site performance. Subsequent calculations would then establish design bases for performance measures such as maximum allowable ground water flow through the seals and minimum allowable ground water travel time. These design bases can then be transposed as specifications for parameters such as permeability and porosity of seal materials.

In applying this general approach for developing design bases and specifications to a repository in salt, it is first appropriate to consider a number of special characteristics of salt as a repository host formation:

1. At repository depths salt is considered free of fractures so that the penetrations may represent virtually the only credible pathway for ground water flow and radionuclide migration.

2. Halite is highly soluble in ground water unsaturated with respect to sodium chloride. Even a minor pathway that exists between the waste and a water source could be enlarged by dissolution and could eventually breach the repository.

3. Salt deforms by creep under relatively low stresses and temperatures. The result is that penetrations in the repository will tend to close with time and crushed salt placed in the penetrations will consolidate. Limited experimental data indicate that crushed salt will recrystallize as it consolidates forming a monolith indistinguishable from the salt forming the walls of the penetration.

It is implicit from the first two of these special characteristics that penetration seals in salt should be as impermeable as is reasonably achievable. An implication of the third special characteristic is that it is feasible, at least in the long term, to achieve very low permeabilities using salt as the major seal material.

Following this reasoning, it is argued that seals in salt are special cases to be considered separately from seals in permeable or fractured formations such as basalt, tuff, or granite. Specifically, a preliminary design basis for seals in salt can be developed without recourse to rigorous modeling. This preliminary design basis is simply that the water flow through the seal system (taking into account the interface between the seal material and the host rock and any disturbed zone in the host rock) should be as low as is reasonably and economically feasible.

In principle, this design basis is achieved by using salt as the major seal material and by relying on creep closure to seal the penetrations by consolidating and recrystallizing the salt. Three important points must also be considered:

1. The design should be time-phased, i.e., some seal components must be designed to limit water flow immediately following construction and for as long as is required for salt consolidation to become effective.

2. Relatively insoluble seal materials are required for locations near sources of water.

3. Special attention must be paid to the interface between seal materials and the host rock.

This design basis is intended for use in the interim period until site specific performance assessment modeling has been completed. This modeling should address potential release scenarios and, as described above, should determine the relative importance of the seals in the whole repository system. In addition, modeling is required to determine the volume of ground water that could enter the repository without resulting in an unacceptable radionuclide release. This maximum acceptable ground water flow rate could directly indicate the maximum permissible initial permeability for the seal system.

2.0 REFERENCE CONDITIONS

2.1 REPOSITORY DESIGN

Penetration seal designs are referenced to the conceptual design for a repository in bedded salt (designated NWTSR-2) developed by Kaiser Engineers (1978). This repository was designed for the disposal of canistered spent-fuel assemblies and low-level waste drums. The design was referenced to a generic bedded salt stratigraphy with a single mine level at 610m (2000 feet) depth.

The main features of the repository design of relevance to sealing are as follows:

- The repository floor is located at a depth of 610m which (for the WIPP stratigraphy) is about 350m below the top of the salt (see Section 2.2).
- Shafts are located in a shaft pillar removed from the waste storage areas (Figure 2-1). The minimum separation between a shaft and the area for permanent waste storage is about 600m.
- Four shafts are used with excavated diameters ranging from 3.2m to 7.3m.
- Shafts will be fully lined from the surface to the repository depth.
- Access tunnels connecting the shafts to the repository have dimensions 5.5m wide by 3.4m high.

2.2 SITE GEOLOGY

At the time of writing, a site in bedded salt for a commercial waste repository has not been selected. For purposes of using site-specific geologic information, penetration seal designs are referenced to the stratigraphy and hydrology of the WIPP site in southeastern New Mexico. Detailed site characterization studies of the WIPP site are described in the Geological Characterization Report (Powers et al, 1978), the Final Environmental Impact Statement (USDOE, 1980a), and the Safety Analysis Report (USDOE, 1980b), for the WIPP project.

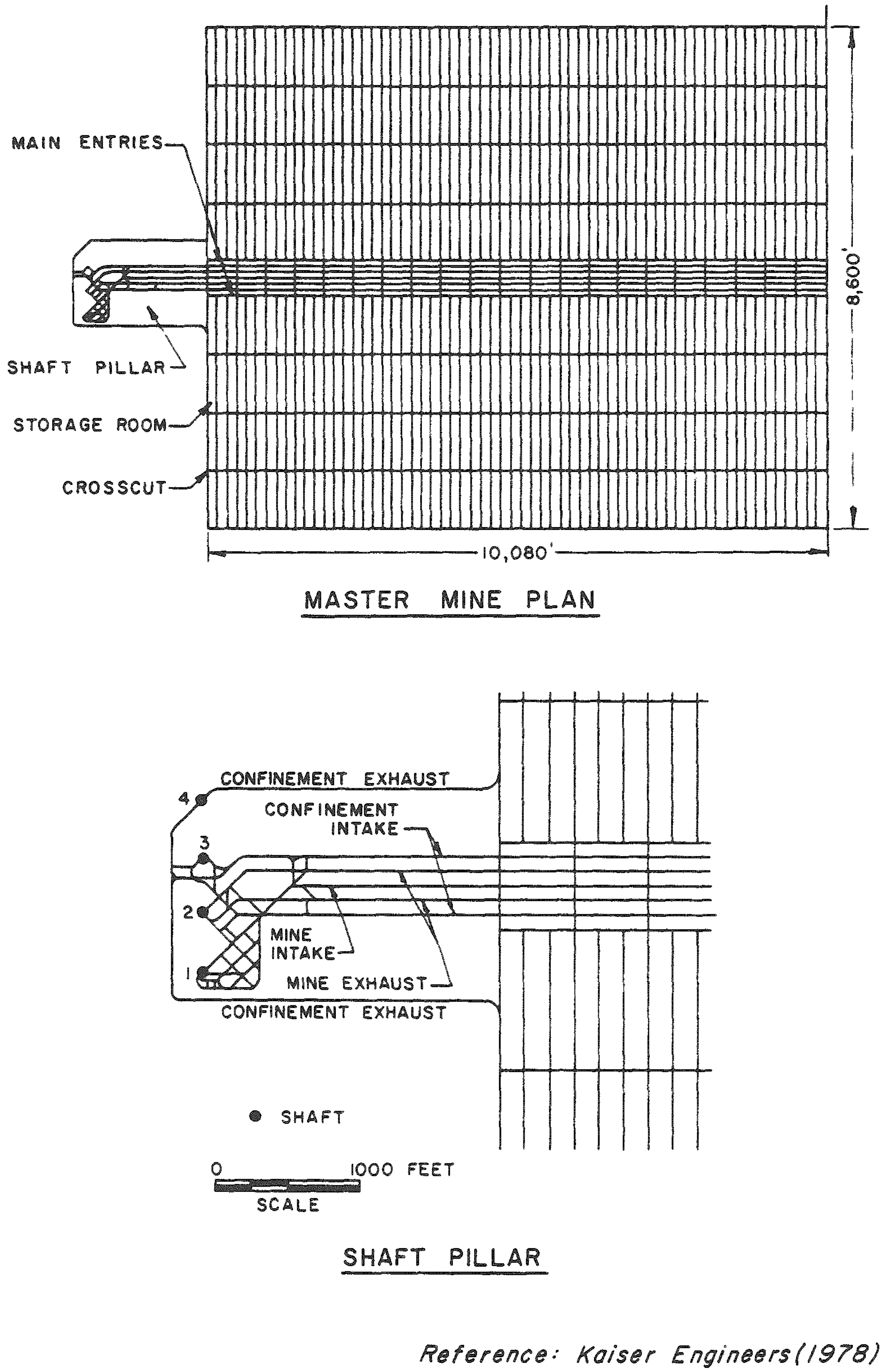

Figure 2-1. NWTSR-2 Repository in Bedded Salt - Underground Layout

2.2.1 Stratigraphy and Hydrology

The stratigraphy obtained from two borings, ERDA-9 and B-25, at the center of the WIPP site is shown in Figure 2-2 together with approximate relative permeability values obtained from a number of borings within the site boundaries. Permeability data are summarized in Table 2.1 and are discussed in more detail in D'Appolonia (1981).

Aspects of the WIPP site stratigraphy and hydrology relevant to sealing have been reviewed in detail in a previous report (D'Appolonia, 1981). Important sealing considerations (illustrated in Figure 2-3) are summarized below:

- The nominal repository horizon is overlain within the Salado Formation by approximately 350m of relatively impermeable halite with interbedded anhydrite, polyhalite, siltstone and thin clay seams in the following approximate proportions (in ERDA-9):

Halite (including argillaceous halite)	89 percent
Anhydrite	6 percent
Polyhalite	3 percent
Sandstone/Siltstone	1.5 percent
Clay	0.5 percent

  The repository is underlain by a similar sequence approximately 265m thick, and by 500m of relatively impermeable halite, anhydrite, and limestone in the Castile Formation.

- Some zones in the Salado contain potash minerals including sylvite, langbeinite and carnallite. These minerals are soluble in halite solutions and may wash out during drilling of boreholes or shafts if special precautions are not taken.

- The contact between the halite of the Salado Formation and the siltstones and carbonates of the overlying Rustler Formation is water-bearing in the area to the west of the site, but is not believed to be water-bearing within the site. Prudently, the contact should be regarded as a relatively permeable discontinuity which may control future dissolution and become part of a pathway to the biosphere.

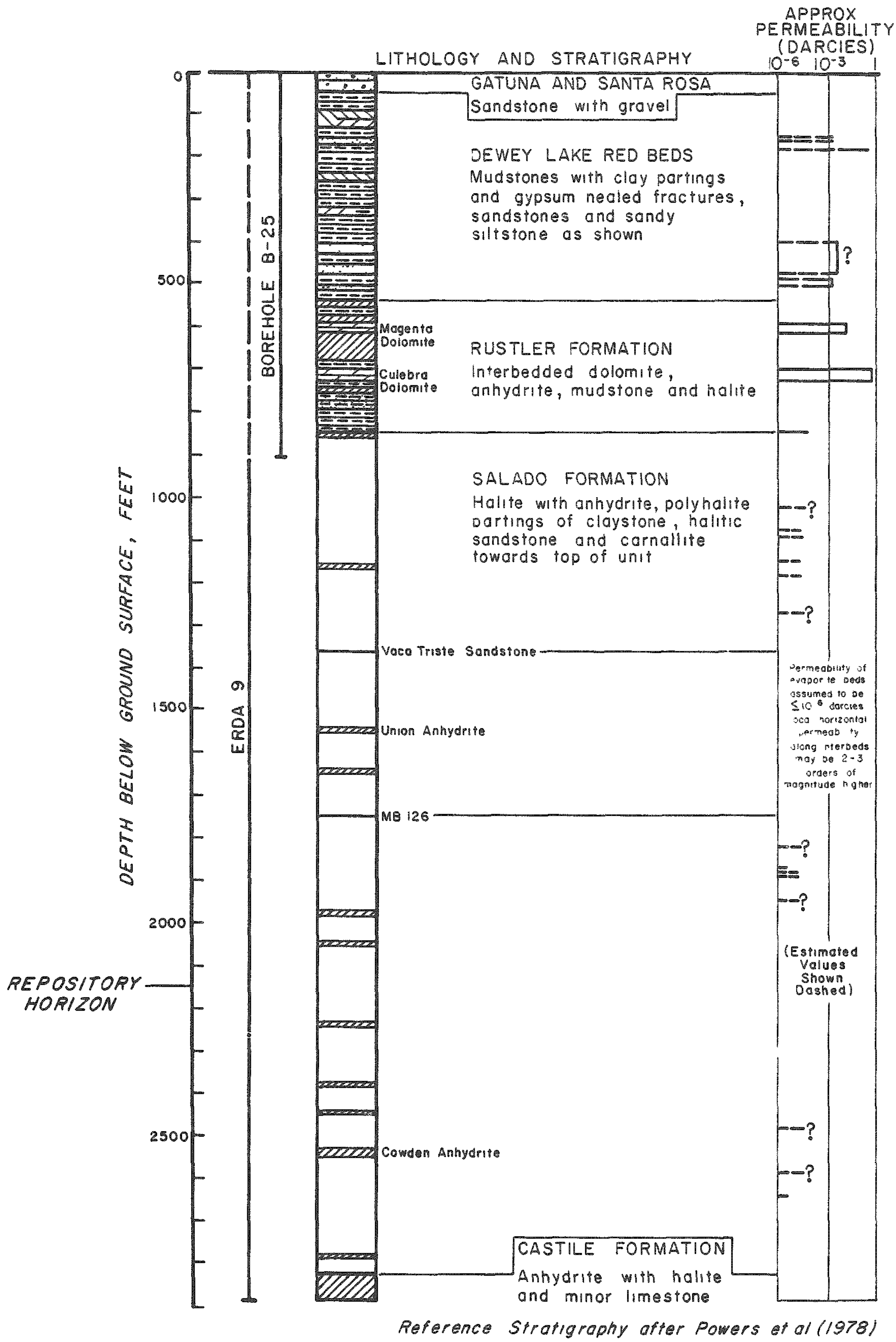

Figure 2-2. WIPP Site Stratigraphy

Table 2-1. Reported Formation Permeabilities - WIPP Site and Vicinity

FORMATION	TEST METHOD	BORING(S)	INTERVAL DEPTH (FT)	MEASURED TRANSMISSIVITY M^2/DAY	MEASURED HYDRAULIC CONDUCTIVITY OR PERMEABILITY	APPROX. EQUIVALENT HYDRAULIC CONDUCTIVITY* (cm/sec.)	REFERENCES
Dewey Lake	packer	various			<0.003-0.7 ft/day	10^{-3}	1
Magenta Dolomite	various, depending on permeability	H-1	562-590	$5x10^{-2}$		10^{-5}-10^{-7}**	2
		H-2a	513-563	$9x10^{-4}$			
		H-3	558-605	$9x10^{-3}$			
		H-4a		$1x10^{-2}$			
		H-5a		$1x10^{-2}$			
		H-6a		$3x10^{-2}$			
Culebra Dolomite	various, depending on permeability	H-1	667-699	$7x10^{-3}$		10^{-3}-10^{-6}**	2
		H-2b		$4.6x10^{-2}$			
		H-3		2			
		H-4b		$8x10^{-2}$			
		H-5b		$8x10^{-2}$			
		H-6b		7			
		P-14	573-601	$1.3x10^{-1}$			
		P-15		$1x10^{-2}$			
		P-17		$9x10^{-2}$			
		P-18	912-940	$9x10^{-5}$			
		W-30		$3x10^{-2}$			
	pump test	Project Gnome	500-530	43.4			3
Rustler-Salado Contact	various, depending on permeability	H-1		$3x10^{-5}$		10^{-8}-10^{-9}***	2
		H-2c		$9x10^{-6}$			
		H-3		$3x10^{-5}$			
		H-4c		$6x10^{-5}$			
		H-5c		$3x10^{-6}$			
		H-6c		$3x10^{-4}$			
		P-14	676-700	$5x10^{-3}$			
		P-15		$4x10^{-5}$			
		P-17		$2x10^{-5}$			
		P-18	1076-1100	$3x10^{-6}$			
		W-30		$2x10^{-2}$			
Salado	drillstem test	ERDA-9	2524-2635		0.0025 md	10^{-8}-10^{-10}	4
	drillstem test		2635-2725		0.002-0.025 md		
	drillstem test		1455-1498		0.0007 md		
	guarded straddle packer	AEC-7	2214-2314		0.010-0.013 md		5
	guarded straddle packer	AEC-7	1819-1919		0.003 md		
	single packer	AEC-7	2522-3918		0.001-0.005 md		
	laboratory				<0.001 md		
Castile (anhydrite)	laboratory				0.0001-0.001 md	10^{-9}-10^{-10}	4
	drillstem test	AEC-8			0.0015 md		

References:
1. USDOE, 1980b
2. Mercer & Gonzales (1981) see also Mercer & Orr (1979)
3. Cooper & Glanzman, 1971
4. Sandia, 1977
5. Sandia, 1979

* Expected values in WIPP shafts based on existing data from boreholes within Control Zone II.
** Assumes saturated thickness = 25 ft.
*** Assumes saturated thickness = 3-30 ft.

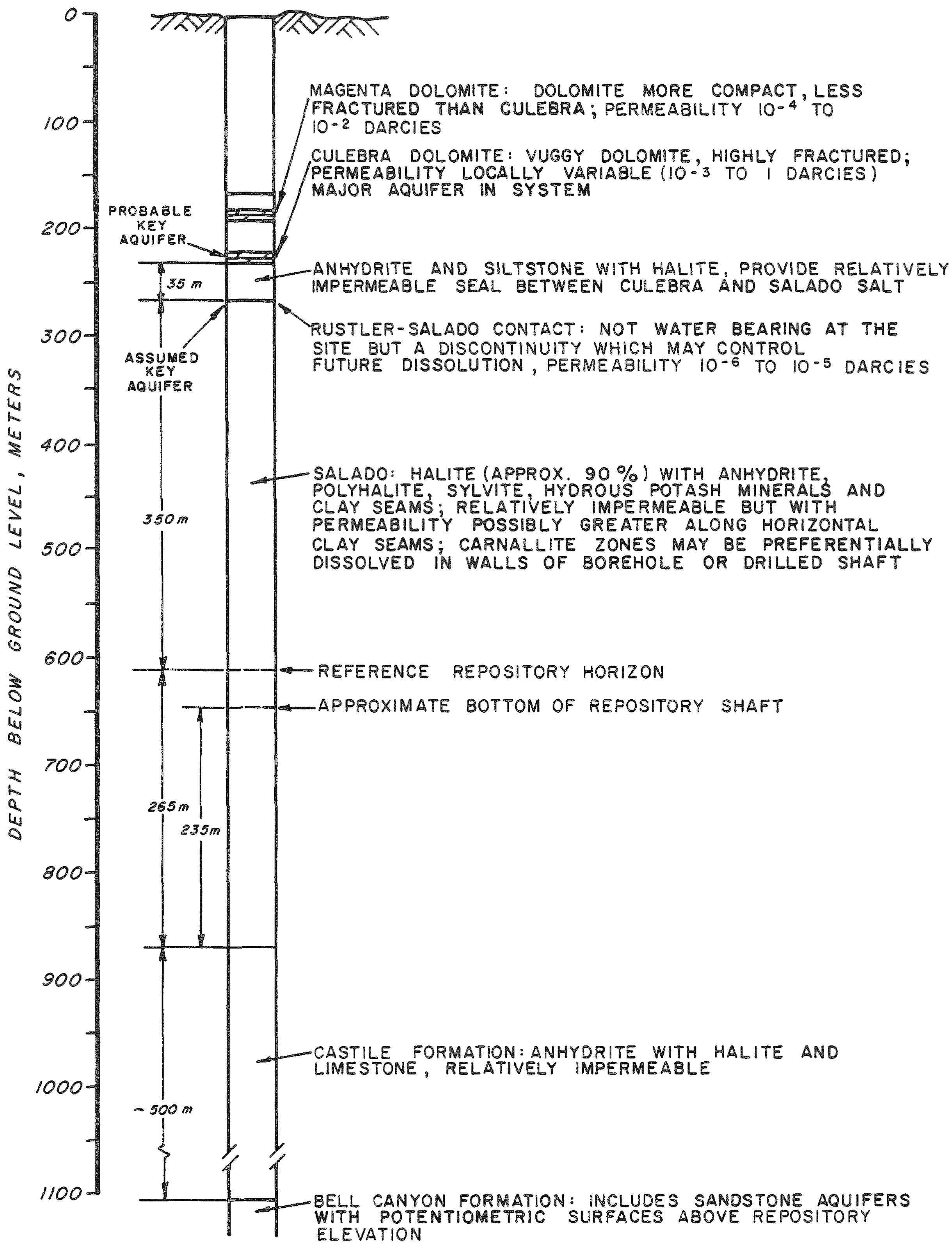

Figure 2-3. Reference Stratigraphy for Penetration Seals in Bedded Salt

- Two water-bearing dolomites, the Magenta and Culebra, occur within the Rustler Formation. The Culebra is the more permeable (Table 2.1) and occurs lower in the section. Permeability in the Culebra is controlled by fractures and vugs and is probably extremely variable even within the site boundaries. Ground water in the Culebra and Magenta is unsaturated with respect to sodium chloride (see Section 2.2.2.5).

- The Culebra and the Rustler-Salado contact are separated by over 30m of anhydrite, siltstone and mudstone. At the site, it is likely that there is little or no communication between the Culebra and the top of the Salado. Similarly, there is probably little direct communication between the Culebra and Magenta.

- The Magenta is overlain by anhydrite and gypsum of the upper Rustler, and mudstones, siltstones and sandstones in the Dewey Lake Red Beds. This sequence above the Magenta includes permeable sands but these zones have less significance for sealing compared with the underlying Rustler aquifers.

These considerations are related specifically to the stratigraphy of the ERDA-9 boring. However, it is likely that the same considerations will apply to all shafts and boreholes within the site boundaries.

2.2.2 Petrology and Geochemistry

The petrology and geochemistry of the WIPP site are summarized in the Geological Characterization Report (Powers et al, 1978) and several other discussions (USDOE, 1980b; Dosch and Lynch, 1978; Serne et al, 1977; Mercer and Orr, 1979). Detailed mineralogical and geochemical studies have been performed on samples from boreholes ERDA-9, AEC-7, AEC-8, and ERDA-6, and ground water quality has been studied in several boreholes.

2.2.2.1 Dewey Lake Red Beds

The Dewey Lake Red Beds are a series of orange to red siltstones, sandstones, and mudstones. Petrographic analyses of selected core from borehole B-25 (near ERDA-9) showed the siltstone to contain mainly quartz and iron-rich (unidentified) clay minerals, with lesser feldspars, opaques, anhydrite, muscovite/sericite, and chlorite. Gypsum veins and disseminated gypsum are found in some intervals. Locally, gypsum and/or anhydrite are found exclusively.

2.2.2.2 Rustler Formation

The Rustler Formation consists of dolomite, limestone, siltstone, and sandstone with lesser amounts of interlayered or associated evaporites, e.g., salt, anhydrite and gypsum. The prominent dolomite strata, i.e., the Magenta and Culebra, are fluid-bearing. The minerals comprising the Magenta are mainly ferroan dolomite, clays and detrital quartz. Ankerite is a minor mineral and gypsum occurs in vugs and fractures. In contrast, the Culebra is composed primarily of dolomite with small amounts of calcite and quartz. Massive anhydrite occurrences in the Rustler Formation contain trace quartz, clays, and opaque minerals. The latter commonly give a banded appearance to the anhydrite.

2.2.2.3 Rustler-Salado Contact

The Rustler-Salado contact is defined by a sharp lithologic change with the dolomitic sandstone of the basal Rustler conformably overlying Salado halite. To the west of the WIPP site where the contact exists as a low-yield aquifer, the Rustler-Salado ground water is high in dissolved materials, probably due to dissolution of halite from the Salado Formation and perhaps from the Rustler.

2.2.2.4 Salado Formation

Petrochemical studies of the site materials (Powers et al, 1978) have emphasized the mineralogy, petrology and chemistry of the Salado Formation and of the uppermost units of the underlying Castile Formation. Overall mineralogy of the Salado Formation was studied in 50 samples from borehole ERDA-9. Eight minerals were commonly present: anhydrite, "clay," halite, loeweite, magnesite, polyhalite, quartz and sylvite.

Detailed mineralogic and petrologic examination of selected intervals of ERDA-9 core from the Salado and the top of the Castile have been performed, with particular attention given to insoluble silicate fractions. Deionized water and EDTA leaches were used to dissolve sulfate and carbonate minerals and leave a silicate residue. Silicate minerals subsequently identified by X-ray diffraction include: quartz, illite, feldspar, chlorite (minor), talc (rare), serpentine (rare), and expandable and mixed-layer clays (major). The occurrence and abundance of some silicates appear to be related to the mineralogy of the evaporite beds, e.g., serpentine commonly occurs in anhydrite and associated halite; illite-smectite mixed layer clay occurs in polyhalite and associated anhydrite only, not in clay beds or polyhalite free zones.

Whole rock chemical analyses of Salado Formation were performed on core material from AEC-7 and AEC-8. Analyses included: weight percent insoluble, SO_3, Na^+, Na_2O, K^+, K_2O, MgO, CaO, SiO_2, Fe_2O_3, Al_2O_3, Cl^-, weight loss on heating (70°C, and higher temperature), major, minor and trace minerals. Mean, standard deviation, maximum and minimum values reported by Sandia for 27 analyses of Salado Formation salt from AEC-7 are shown in Table 2.2. Petrographic observations and calculation of normative mineralogy confirm that halite is the major phase in the soluble fraction, while quartz, clays and hematite occur in the insoluble fractions. The insoluble fraction may make up over 50% by weight of some samples, but in most cases is less than 3% of the total sample weight. Chemical mass balance calculations suggest that the clay minerals include chlorite, talc, and mixed layer illite-montmorillonite. DTA shows no irreversible dehydration of silicate phases below 300°C.

Fluid inclusions and other volatiles bound in the evaporite were studied by Powers et al (1978). Volatiles may include loosely-bound or intergranular volatiles, chemically-bound volatiles (e.g., in hydrated phases) and fluid inclusions. Thermogravimetric analysis was used to demonstrate volatile loss in 35 core samples from ERDA-9 that had been

Table 2-2. Whole Rock Chemical Analyses on Salado Formation Core From AEC-7 (WIPP Site)

Component	Mean	Standard Deviation	Maximum (Depth)	Minimum (Depth)
SO_3	5.21	11.67	46.62 (2537')	0.11 (1403')
Na	34.83	9.08	39.75 (2736')	0.93 (2537')
Na_2O	0.53	1.58	6.63 (1108')	0 (several samples)
K	0.41	0.51	1.91 (1172')	0 (1108')
K_2O	0.18	0.86	4.48 (1108')	0 (several samples)
MgO	1.10	2.58	13.02 (2537')	0.01 (2716')
CaO	1.72	4.77	25.13 (1172')	0.02 (1403')
SiO_2	1.25	3.05	13.98 (2537')	0 (several samples)
Fe_2O_3	0.10	0.23	1.13 (2537')	0 (several samples)
Al_2O_3	0.26	0.68	3.26 (2537')	0 (several samples)
Cl	53.82	13.87	61.00 (2716')	2.63 (2537')

All values in weight percent.
Depths in feet
Reference: Powers et al (1978).

previously studied by X-ray diffraction. Water was associated exclusively with weight losses below 100°C. Between 300-500°C, weight loss was considered to be due to decomposition of volatile-bearing mineral phases. The volatile species released is a function of temperature, although in one sample where a high weight loss was registered, H_2O and CO_2 were released over the entire temperature range studied (50-300°C). At temperatures between 100-300°C, N, N_2, CH_3, O, OH, F(?), and HCl are evolved as are SO_2 and SO_3 due to sulfate decomposition. A major event of volatile release occurs at 250°C and probably indicates rupturing of fluid inclusions trapped in evaporite minerals. Alternatively, it might be associated with decomposition of polyhalite which breaks down in the range 170°-300°C, and releases up to 6% of its weight in water. Low temperature (<100°C) production of volatiles is almost certainly due to release of substances adsorbed on hygroscopic minerals.

The results of static heating experiments appear to indicate that release of adsorbed water is primarily from clay mineral surfaces. Specifically, heating cores from AEC-7 and AEC-8 to 100°C produced minimal weight loss when samples were composed entirely of halite and/or anhydrite. The presence of clays, however, increased significantly low temperature weight loss.

Fluid inclusions in ERDA-9 core were studied in "representative" sections and in unusual sections in which inclusions were visible. Two sections from AEC-8 and the Kerr-McGee potash mine near an igneous dike were also considered. Study methods included measuring inclusion volumes, homogenization temperatures using heating stage, freezing point depression using the cooling stage, estimation of noncondensible gas pressure using the crushing stage, microscope examination of water-insoluble residues from inclusions, and inclusion decrepitation. Cloudy halite crystals commonly contain approximately 1 volume % fluid due to dispersed, small volume fluid-filled cavities. Larger inclusions are more rare and appear to occur in coarser grained halite. This coincidence would suggest that larger inclusions have resulted from recrystallization of the host salt. Some larger inclusions contained daughter crystals which are unidentified. Other larger inclusions contain gas bubbles under pressure. Air-filled inclusions, liquid-filled under natural conditions, have also been identified. Leakage along grain boundaries during coring and handling probably caused dessication of these inclusions. Fluids in the inclusions are strong bitterns containing salts in addition to NaCl, and are compositionally variable from inclusion to inclusion. Gases present in the inclusions are usually condensable and non-corrosive.

2.2.2.5 Ground Water Quality

Table 2.3 shows the major dissolved species concentrations for ground waters collected from fluid-bearing zones in the Magenta Dolomite, Culebra Dolomite, Rustler-Salado contact and Delaware Sand (Bell Canyon Formation). The Magenta ground water contains significantly less dissolved solids than deeper ground water, and its composition varies more widely from place to place, particularly with respect to NaCl. Variation in the water composition probably reflects the fractured nature of the aquifer. The Culebra Dolomite water shows an eastward increase in TDS, but considerable areal variation is also present. High ion concentration suggests communication between the Culebra and Rustler-Salado aquifers. The latter contains waters approaching NaCl saturation due to dissolution of halite. Deep aquifers, such as sandstones in the Bell Canyon, also bear dense brines.

2.2.2.6 Sorptivity of Evaporites and Fluid-Bearing Formations

The sorptivity of the Culebra and Magenta Dolomite members of the Rustler Formation and the Salado Formation evaporites are reported in terms of sorption coefficients (Kd's) with respect to several elements in Tables 2.4 to 2.6. The data shown are for key radionuclides or their analogues. For testing, several fluids were synthesized to be chemically similar to naturally occurring ground water at the WIPP site. All analyses shown were obtained from batch experiments except those identified as column (dynamic) tests in Table 2.6. Conditions were

Table 2-3. Water Quality Data - WIPP Site

Constituent *	Formation and Boreholes Sampled			
	Magenta H-1, H-2a H-3	Culebra H-1, H-2b H-2c, H-3, P-14, P-15 P-17, P-18	Rustler-Salado Contact H-1, H-2c H-3, P-14	Delaware (Bell Canyon) AEC-8
pH	7.2-8.6	6.0-1.02	5.9-7.9	6.0
Temperature (°C)	22.0-22.5	20.5-24.5	20.5-24.5	30.0
Calcium magnesium hardness	2,700-5,000	2,200-80,000	6,400-160,000	35,000
Total dissolved solids	10,300-29,700	8,890-118,000	311,000-327,000	189,000
Sodium (Na)	2,700-9,300	2,100-30,000	56,000-120,000	55,000
Potassium (K)	81-840	91-6,200	1,300-17,000	860
Calcium (Ca)	320-1,200	770-5600	570-18,000	10,000
Magnesium (Mg)	170-480	63-16,000	1,200-30,000	2,500
Iron (Fe)	0.04-0.22	0.02-17	1.5-2.5	23
Manganese (Mn)	0.00-0.95	0.12-4.5	3.4-78	14
Boron (B)	0.22-13	0.7-100	1.7-150	53
Bicarbonate (HCO_3)	51-93	59-357	199-675	420
Sulfate (SO_4)	2,400-3,600	980-11,000	370-10,000	240
Chloride (Cl)	4,100-15,000	2,800-80,000	180,000-210,000	120,000
Carbonate (CO_3)	0	0-24	0	0
Fluoride (F)	1.8-2.0	0.5-2.0	-	1.2
Silica (SiO_2)	1.7-6.4	0.6-33	0-2.0	3.6
Nitrate + Nitrite (N)	0.04-0.08	0.01-0.81	0.29-1.1	0.11
Orthophosphorus (P)	0.01-0.04	0-0.4	0-0.08	0.05

Summarized from Mercer and Orr (1979)
*Units mg/l except where shown

Table 2-4. Sorption Coefficients (Kd) in ml/g for Magenta and Culebra Dolomite with Respect to Various Elements

Rock	Np	U	Eu	Pu	Cs	I	Tc	Sr	pH	Fluid*	Reference
Magenta Dolomite			$>5 \times 10^3$		<1	0-1.5	0-1.5	1	6.5-6.9	A	1
Same			$>5 \times 10^3$	5.4×10^3	<1	<1	<1	1	6.5-7.8	B	1
Same			$>10^4$	2.4×10^3	4	0-1.5	0-1.5	5	7.5-8.2	C	1
Culebra Dolomite			$>10^4$		<1	<1	<1	<1	6.5-6.9	A	1
Same			$>10^4$	2.1×10^3	1-2	<1	<1	1-2	6.5-7.8	B	1
Same			$>10^4$	7.3×10^3	7-10	<1	<1	4-5	7.5-8.3	C	1
Magenta Dolomite 7/13/47 days			451/640/ 9873		2656/2345/ 2237			5.6/5.3/8	8.1-8.5	Dist. H_2O	2
Same 4/14/47 days			48/56/34		-.3/.3/-.5			-.3/1/.4	6.4-6.75	XA	2
Same 5/13/40 days			55/46/31		.1/-.2/-.2			-.1/.6/-.4	6.6-7.0	XB	2
Culebra Dolomite 7/13/47 days			359/639/ 45584		1739/1809/ 110			12.4/10.3/8	8.32-8.68	Dist. H_2O	2
Same 4/14/47 days			87/97/50		-.6/-.1/-.2			-.8/.7/.6	6.4-6.75	XA	2
Same 5/13/40 days			54/61/31		.2/-.1/-.1			-.3/.6/.3	6.6-7.08	XB	2
Culebra Dolomite 16 days					1.3±1.09		.24±.97	.85±.86	6.52±.03	B	2
Same					13.6±2.4		.47±.84	1.02±1.41	7.51±0.01	C	2
Same 5/8 days		4.5±2.7/ -0.9±1.5							7.7/6.5	B	2
Same	22.4±5.4/ 11.3±1.3								6.9/6.6	B	2

REFERENCES: [1]Dosch and Lynch (1978)
[2]Serne et al (1977)

*WIPP Synthetic Brines A, B, Solution C
Other Brines XA, XB
Compositions given in Serne et al, 1977, Appendix B

Table 2-5. Sorption Coefficients (Kd) in ml/g for Salado Formation Evaporite Lithologies with Respect to Several Elements

Rock	Pu	Am	Cm	Cs	Sr	I	Tc	Gd	Eu	Other	pH	Fluid*
ERDA-9 halite 2056'	17	306	354								7.0-7.1	?
Same, based on wt. insoluble	10^4	1.8×10^5	2.1×10^5								7.0-7.1	?
AEC-8, clay, 2186.6'				<1	<1	<2	<2	>2500	>2500	Ru: 150-180	6.5-7.0	A
Same				4-6	<1	<1	<1	$>10^4$	$>10^4$	Ru: $>2 \times 10^3$	6.5-7.7	B
Same				80-120	3-6	<1	<1	$>10^4$	$>10^4$	Ru: >1000	7.5-7.8	C
Same	4×10^4	1100	1.9×10^4								6.5-8.0	B
Same	1.8×10^5	3500	4.2×10^5								7.5-8.4	C
ERDA-9 poly-halite, 2304'				<1	5-10		<1		10	Ce: 20 Sb: <1	6.5-7.0	A
Same				<1	19-22		<1		430-700	Ce: 50-55 Sb: 0.9-1.5	6.5-7.2	B
Same				<1	35-40		<1		100-200	Ce: 40-60 Sb: 3-4	7.5-7.6	C
Cowden Anhydrite	6700	290	4200					$>10^3$	$>10^3$	Ce: $>10^3$	6.5-7.9	B
Same	7.7×10^4	2200	1.8×10^5								7.5-8.2	C
AEC-8, clay, 2725'				4-9	<1	0-3.5	3.5-4.5	280-400	$>10^3$	Ru: 90-120	6.6-7.0	A
Same				3-6	<1	<1	<1	$>10^4$	$>10^4$	Ru: $>10^3$	6.7-7.4	B
Same				34-40	30-45	0.5-4	0.7-1.5	>3000	$>10^4$	Ru: $>10^3$	7.5-8.0	C
Same	7.2×10^4	310	2.7×10^3								6.5-7.8	B
Same	4×10^4	2300	1.6×10^5								7.4-8.4	C
ERDA-9, halite, 2611'	59	11	56								7.0-7.3	Saturated NaCl solution
Same, based on wt. insoluble	2.11×10^4	3.8×10^3	2×10^4									Saturated NaCl solution

*WIPP Synthetic Brines A, B, Solution C; Compositions given in Serne et al, 1977, Appendix B.
Reference: Dosch and Lynch (1978)

Table 2-6. Column (Dynamic) Sorption Determinations on WIPP Site Halite

Days	% Initial Activity in Solution	
	^{85}Sr	^{144}Ce
0	100	100
1	98	27
4	97	0.9
8	98	0.0

Notes: ERDA-9 halite, 2611' depth
Saturated NaCl Solution

Reference: Dosch and Lynch, 1978

oxidizing. Most of the Sandia (Powers et al, 1978; Dosch and Lynch 1978) experiments were run with fluids containing one isotope spiked approximately to 1 mCi/ml. Serne et al (1977) usually spiked influent solutions with more than one isotope, at so-called "realistic" concentrations. The data show that I, Tc, Cs, U, and Ra are poorly sorbed by Los Medanos geologic media, whereas Pu, Am, Cm, Sb, Gd, Eu, and Ru are more strongly sorbed (higher Kd values) under the experimental conditions. It should be noted that impurities, notably clays, are probaby the most effective sorbers in the evaporite samples studied.

2.3 HOST ROCK PHYSICAL, MECHANICAL AND THERMAL PROPERTIES

Extensive testing of physical, mechanical and thermal properties of halite, anhydrite, and polyhalite from the WIPP site has been conducted by Sandia. Values used in thermomechanical analyses in this report are given in Appendix A.

2.4 IN SITU STRESSES AND REPOSITORY TEMPERATURES

2.4.1 In Situ Stresses

Stress conditions are assumed to be hydrostatic and are calculated according to a stress gradient of 0.023 MPa/m (1 psi/foot) depth. At the reference repository depth of 610m, the in situ stresses are thus 13.8 MPa (2000 psi) in all directions.

2.4.2 Temperatures

Figure 2-4 shows temperature histories for three key seal locations within the repository: a panel seal placed within the repository, a boundary seal placed in the shaft pillar 100m from the edge of the storage area, and the base (plinth) of a shaft. The calculations are for both spent fuel and commercial high level waste with heat loading densities of $15W/m^2$ for the plinth and the boundary seals. In the panel seals temperatures are calculated for densities of $15W/m^2$ and and $25W/m^2$ to account for locally higher loadings close to the storage rooms. All analyses are based on an initial temperature of 34°C (Raines et al, 1981). Details of the analytical method are given in Appendix A.

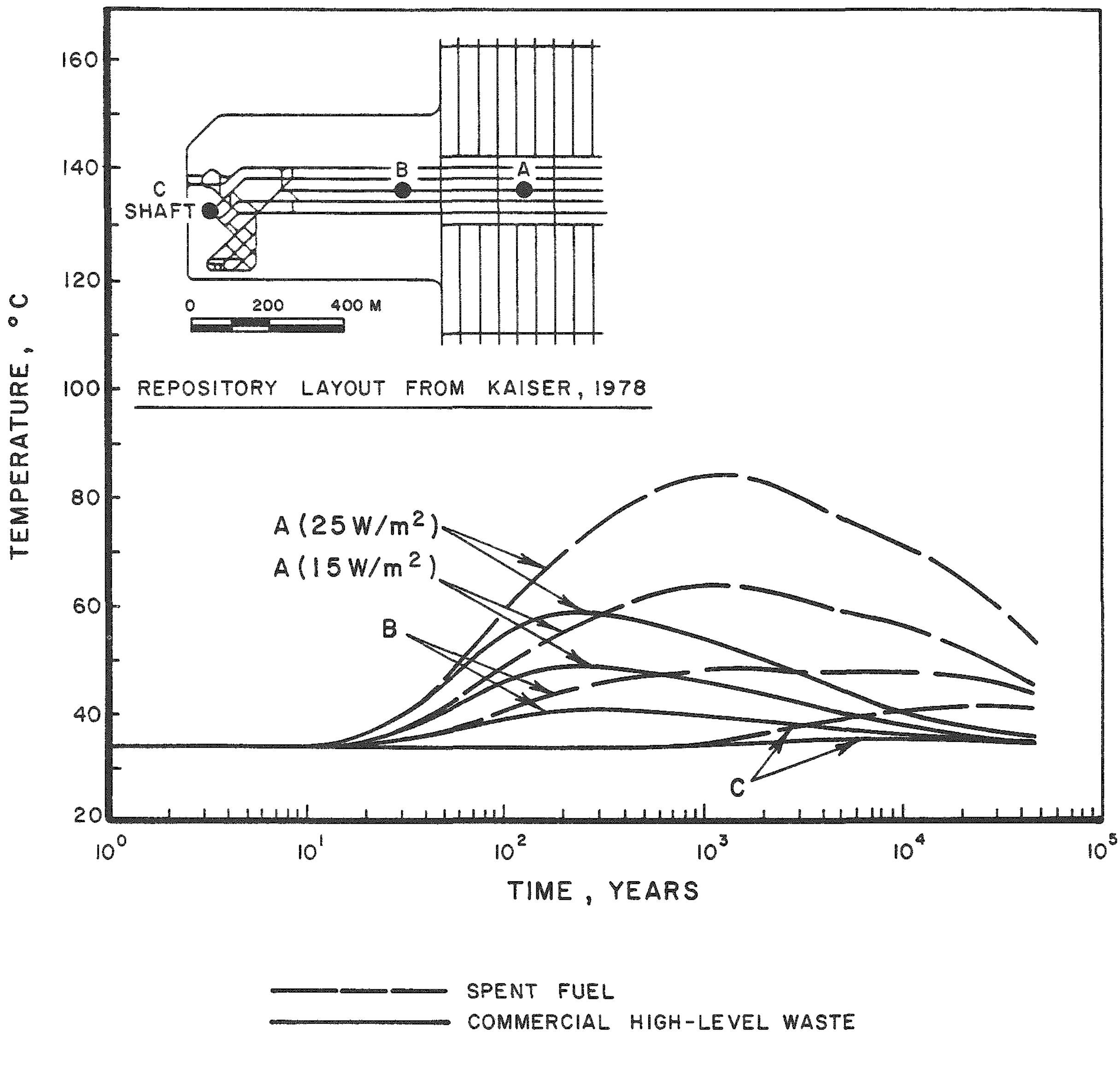

Figure 2-4. Approximate Temperature Histories for Potential Seal Locations - Reference Salt Repository

3.0 SCHEMATIC DESIGNS FOR PENETRATION SEALS

Schematic designs for a repository in bedded salt are described in this chapter. As described in Chapter 1.0, schematic designs are working designs that will be updated as additional laboratory and field data are collected. Sections 3.1 and 3.2 consider shaft and tunnel seals, and Section 3.3 borehole seals, all referenced to the WIPP site stratigraphy and the NWTSR-2 repository design. Section 3.4 briefly considers the applicability of the designs to other salt sites.

The schematic designs described in this chapter are based in part on analyses (presented in Appendix A) of crushed salt consolidation and stress buildup around bulkheads placed in salt. These analyses are encouraging from a sealing viewpoint in that they indicate that crushed salt should consolidate to the point at which its properties are essentially the same as those of undisturbed intact salt. For WIPP site salt, and for the reference repository conditions described in Chapter 2.0, consolidation is predicted to occur within a period ranging from 400 to 1000 years depending on location within the seal system. Within the same period stresses around bulkheads are predicted to build to levels (close to the in situ hydrostatic stress) at which any fractures caused by excavation should be healed.

The analyses presented in Appendix A are preliminary, in that they are based on sparse laboratory test data and that they incorporate several simplifying assumptions. Moreover, the rate of consolidation is found to depend primarily on the creep properties of the intact salt forming the penetration walls, and on the depth and temperature of the repository. The present study considers two salts, one which creeps relatively slowly (WIPP site), and one which creeps at a faster rate (Avery Island dome salt). Further analyses are required to confirm that room closure rates for candidate repository sites (taking into account proposed repository depths as well as creep properties) are comparable to those considered herein.

3.1 GENERAL CONSIDERATIONS FOR SHAFT AND TUNNEL SEALS

The design approach for repository seals is based on three fundamental principles:

- Multiple Function
  Seals are required primarily to prevent or retard migration of radionuclides from the repository to the biosphere through the penetrations used for access to the repository. In order to achieve this primary function, seal components may have other supporting functions, such as prevention or retardation of ground water flow into the repository (particularly in salt), or structural support in order to prevent excessive deformation of overlying formations. Most seal components will serve more than one function.

- System Design
  A potential pathway for radionuclide migration is through the system of mined openings, from the storage rooms, via the access tunnels, and into the shafts. The network of interconnected mined openings is thus considered as a single system, even though the functions of seal components vary according to the specific type of mined opening (related to location in the system) under consideration.

- Multiple-Component Designs
  The seal system is composed of a number of different components each of which is designed for a specific function (or combination of functions), and specific loading conditions as determined by the site geology and location in the repository. Components are repeated in the design in order to provide a degree of redundancy, and to safeguard against failure of an individual component.

3.1.1 Seal Functions

For any repository, the primary function for the seal system is the limitation of radionuclide migration through the penetrations. In principle, this may be achieved solely by restricting ground water flow, or by a combination of restricting ground water flow and retarding radionuclide migration by chemical or physical means (e.g., by sorption, or by molecular sieving as with zeolites). For a repository in salt, there are several reasons for proposing that major emphasis should be given to restricting ground water flow, with retardation considered only redundancy in the system. First, regardless of the means by which radionuclides might be retained within the repository, a primary function for penetration seals in salt must be exclusion of water. Salt is highly soluble and if a pathway existed between the repository and an aquifer, water (or unsaturated brine) could enlarge the pathway by dissolution. Eventually, large volumes of water could enter the repository and gain access to the waste.

Other reasons for emphasizing water exclusion in salt also relate to properties of the salt. At repository depths, salt is likely to be unfractured and essentially impermeable. If the seals can also be made essentially impermeable the waste will be completely protected against water incursion. (In contrast, a rock such as granite is permeable and water will enter the repository regardless of the performance of the seals.) A further significant property of salt is its high capacity for creep under relatively low stresses and temperatures. As described in detail in later sections, there is evidence that fractures in salt will heal as a result of creep, and that crushed salt will consolidate and possibly even recrystallize, at temperatures and pressures that will be obtained in a repository. This means that it is realistic to consider and construct essentially impermeable seals in salt. There appears to be little incentive, therefore, for engineering seals to be highly sorptive, although it may be desirable to include sorbent materials as a portion of the seal system, especially if these materials can also be engineered to possess a low permeability.

It is thus proposed that the primary function for all or most components in the seal system will be water exclusion. A secondary function will be to provide structural support to limit long-term rock mass deformations which could lead to disruption of overlying formations. Despite this similarity in primary function, however, components within the seal system will differ according to location and specific function. Major elements of the seal system for a repository in salt are as follows:

> Shaft seals prevent incursion of water from overlying aquifers. Because they are placed close to sources of unsaturated water, they must be composed of dense, insoluble materials.
>
> Tunnel seals placed in the access tunnels joining the shafts to the repository also prevent incursion of water, and prevent outflow in the event that the repository is breached.
>
> Panel seals are placed in cross-cuts joining storage panels to the main access tunnels in order to isolate individual storage panels.
>
> Storage room backfill is placed in all the waste storage rooms. Its function is to limit deformations and, in the long-term, to form an impermeable monolith enclosing the waste.

Specific component functions will be considered in more detail in Section 3.1.3, following consideration of candidate seal materials.

3.1.2 Materials Considerations for Seals in Salt

The choice of materials for seal components must take into account a number of factors, including:

- the function of the component (e.g., impermeability and/or structural support), and the period (short or long term) over which it is required to function;
- the environment in which the seal will be placed (e.g., pressure, temperature, ground water chemistry, proximity to waste);
- longevity requirements;
- suitability of the mined rock as a seal material,
- cost;
- construction feasibility; and
- the existing data base for candidate materials;

At present, primary candidate seal materials for a repository in salt are salt (crushed or in brick form), cementitious materials, and earthen materials. Although these materials appear adequate at present, additional or alternative materials will be considered if further investigations and testing indicate their desirability for technical or cost reasons.

3.1.2.1 Salt

At any repository site it is desirable to use as much as possible of the mined rock within the seal system provided that the crushed rock is suitable as a seal material. Not only is the mined rock available at low cost and in more than adequate supply, it must be disposed of at the surface if it is not used to backfill the repository. Also, the crushed rock is obviously chemically compatible with the host formation. As a backfill material in a salt repository, crushed salt has a desirable property in that it should tend to recrystallize under the influence of pressure and elevated temperature forming an homogeneous, relatively impermeable mass. There is, thus, the possibility for isolating the waste within a salt monolith formed by recrystallization of the salt backfill both internally and across the interface to the intact salt.

The consolidation of crushed salt has been examined in the laboratory by Wagner (1980). These tests provide basic data for predicting the degree to which crushed salt will consolidate under a given hydrostatic load. A preliminary indication of the permeability changes that might accompany consolidation is given by data obtained by Shor et al (1981) from tests on consolidated salt, and by Core Laboratories (in Golder, 1977) and Waterways Experiment Station (1963) from tests on intact rock salt. In addition, data given by Wagner (1980) indicate the changes in strength that accompany consolidation. Permeability and strength changes accompanying consolidation of crushed salt are discussed further in Appendix A.

Appendix A also presents an analysis of the consolidation behavior of crushed salt in repository rooms at a depth of 610m. Elements of the analyses include:

- Consolidation occurs in response to creep closure of the rooms. Volumetric closure rates are calculated using a closed-form solution for an infinitely-long cylinder in an infinite medium (Chabannes, 1982). The cumulative closure histories for various points in a repository take into account temperature rises due to waste emplacement.

- Consolidation characteristics for crushed salt are obtained from the references cited above.

- Consolidation is calculated as the change in porosity and build up of stress in the backfill as a function of time. Parametric studies show the influence of initial porosity of the crushed salt and intact salt properties (creep rate) on the degree of consolidation achieved in a given period. The impact of not completely filling a backfilled room is also considered.

Table 3-1 summarizes results obtained for 3 potential seal locations with 2 different waste forms, spent fuel and commercial high-level waste (CHLW). Closure rates are calculated using a secondary creep law for southeastern New Mexico (SENM) salt (Herrmann et al, 1980). The initial porosity of the salt backfill is assumed to be 41% and the final porosity, taken to correspond to intact salt, is 0.6%. All analyses consider an idealized circular opening. Closure rates (and hence consolidation rates) should be more rapid for a rectangular tunnel, although the rate of consolidation may be less uniform throughout the backfill. Further analyses are required to determine whether consolidation will be uniform throughout a rectangular tunnel or whether consolidation at the corners could be slower than in the center of the room.

Little difference is observed between the two waste forms because the temperature histories are similar over the period of interest (Figure 2-4). The initial porosity of the backfill has a significant influence on the time required to achieve consolidation at the base of the shaft but less influence closer to the waste. With a 25% initial porosity,

Table 3-1. Consolidation of Crushed Salt - Summary of Results

Location	Approximate Time to Consolidate to 0.6% Porosity	
	CHLW	Spent Fuel
Base of shaft	840	830
Shaft pillar, 100m from edge of storage area	570	470
Main access tunnel in repository ($15W/m^2$)	380	290
($25W/m^2$)	250	200

the time to achieve 0.6% final porosity is approximately 500 years for the base of the shaft and 200 years for the access tunnel in the repository ($25W/m^2$ heat loading). A very significant input parameter is the creep law for the intact salt. For example, the secondary creep law for Avery Island salt (Mellegard and Senseny, 1981) gives closure rates, and corresponding consolidation rates, approximately an order of magnitude faster than those shown in Table 3-1.

Times for consolidation will be slower than those shown in Table 3-1 if a tunnel is not completely backfilled to the roof. Appendix A presents analyses of the times required to close air gaps of various dimensions for SENM and Avery Island salt. For an access tunnel with dimensions 5.5m wide by 3.4m high, and a seal location 100m from the edge of the storage area, the periods required to close air gaps of 0.3m and 1.0m are approximately 150 years and 350 years respectively (for SENM salt).

These analyses incorporate a number of simplifying assumptions. Nonetheless, they offer positive indication that consolidation of crushed salt should be an effective process for sealing penetrations even at locations removed from the waste. The analyses suggest that it may not be necessary to compact crushed salt backfill to any great degree, especially in the storage rooms and adjacent access tunnels.

Tests to evaluate fracture healing in salt have been conducted at Sandia (Costin and Wawersik, 1980). Preliminary results indicated that significant healing occurred within a few days when samples were heated at up to 100°C and subjected to confining stresses of up to 35 MPa. The Sandia tests evaluated fracture healing in terms of fracture toughness, a parameter which indicates the resistance to crack propagation along an existing fracture. The results do not indicate permeability directly although it appears likely that permeability should be reduced significantly along fractures which exhibit high values (approaching values for intact specimens) for fracture toughness. In the test with the lowest temperature and confining stress (22°C, 10 MPa) the strength along the fracture was in the range 20 to 30 percent of the intact strength. This is considered an encouraging result given the short duration of the test. It is not clear at present whether healing occurs as a result of creep and interlocking of asperities or recrystallization. Further tests to measure permeability of healed fractures are planned as part of future sealing activities.

As a backfill material, crushed salt also has a number of properties which limit its application. Most obviously, salt is highly soluble in fresh water so that it cannot be used as a backfill material in locations, such as in the shafts, where contact with ground water is assured or probable. For the same reason, salt should not be used as concrete aggregate where contact with unsaturated water is possible.

From this discussion it appears that salt is a suitable (and perhaps ideal) candidate material as a general backfill in the repository and in tunnels connecting the repository to the shafts. Creep closure of these tunnels is likely to recrystallize the crushed salt backfill and create an impermeable monolith. Salt is not a suitable backfill material close to sources of ground water, or where in situ stresses and temperatures are low so that consolidation and recrystallization would be very prolonged.

3.1.2.2 Cementitious Materials

Cementitious materials include cement mortars, grouts, concretes and other portland cement based materials. In general, these materials are known to have a range of properties (strength, permeability, durability, etc.) consistent with the requirements for bulkheads and structural fills in the seal system (D'Appolonia, 1980b). At present, two concrete types are being considered - a dense, strong concrete and a low modulus, fracture-resistant concrete. The dense, strong concrete would use a cement base similar in type and composition to the BCT-IFF grout mix developed for the Bell Canyon Test performed by Sandia (Gulick et al, 1980). The BCT-IFF grout is composed of Class H portland cement with fly ash additive and a proprietary expansive agent. Properties of the grout include compressive strength of up to 90MPa and hydraulic conductivities as low as 10^{-9} cm/sec. For concrete formulation, a site-derived aggregate, possibly dolomite, would be mixed with cement in a ratio near 1:3 using a brine-mixing water for emplacement in halite. The resulting concrete would be slightly expansive, with a hydraulic conductivity of the same order as the grout. Further testing is required to determine concrete properties.

A low modulus, fracture-resistant concrete may be a desirable alternative to a strong, rigid material for some applications. Such a concrete would have a relatively low compressive strength but a high strain to failure. The concrete should then creep in response to stress instead of fracturing. Two types of concrete have been suggested for this purpose, an elastomeric polymer concrete, and portland concrete either with a relatively soft aggregate such as a greywacke or with bentonite added to the cement. At present, a portland formulation is of greater interest because of long-term uncertainties associated with polymer stability and because many polymers are toxic and expensive.

3.1.2.3 Earthen Materials

Natural earth materials include crushed rock, gravel, sand, and clay which may be mixed together as "earthfill" or graded to a narrow grain size range. In general, natural materials which are compatible (mineralogically similar) with the host rocks at the site may be expected to be durable. Accordingly, clays similar in composition to the clay seams occurring in the Salado salt are primary candidates. Clays are both sorptive and compressible, and appear suitable as a major component for shaft or tunnel backfill. Clay-rock or clay-sand composites may have hydraulic conductivities ranging from 10^{-4} cm/sec to 10^{-12} cm/sec depending on factors such as the proportion and type of clay and the degree of compaction. In salt, the compaction of clays will be increased by the closure of the rooms. In the long term, this should tend to reduce permeabilities. Studies to evaluate the general suitability of clays for repository sealing are in progress at D'Appolonia and Pennsylvania State University.

3.1.3 Seal Components

Two basic types of seal components are required in the seal system, bulkheads and backfill. The specific functions of these basic components are discussed in the following sections. Figure 3-1 illustrates the use of bulkheads and backfills as the basic components in the shaft and tunnel seal system.

3.1.3.1 Bulkheads

Bulkheads are relatively impermeable seal components interspersed with sections of backfill in both the shafts and access tunnels. Their primary function is to limit ground water flow internally within the seals as well as at the seal-rock interface and in the disturbed zone. Sorption will not be an important function. Generally, bulkheads are designed to be effective immediately or soon following emplacement. This provides an effective short-term (and possibly long-term) seal during the period that the crushed salt backfill is consolidating. An important feature of bulkheads is that they will be constructed according to stringent specifications regarding materials and construction techniques. Also, in contrast to entire seal systems, individual bulkheads are relatively small structures that can be constructed and tested

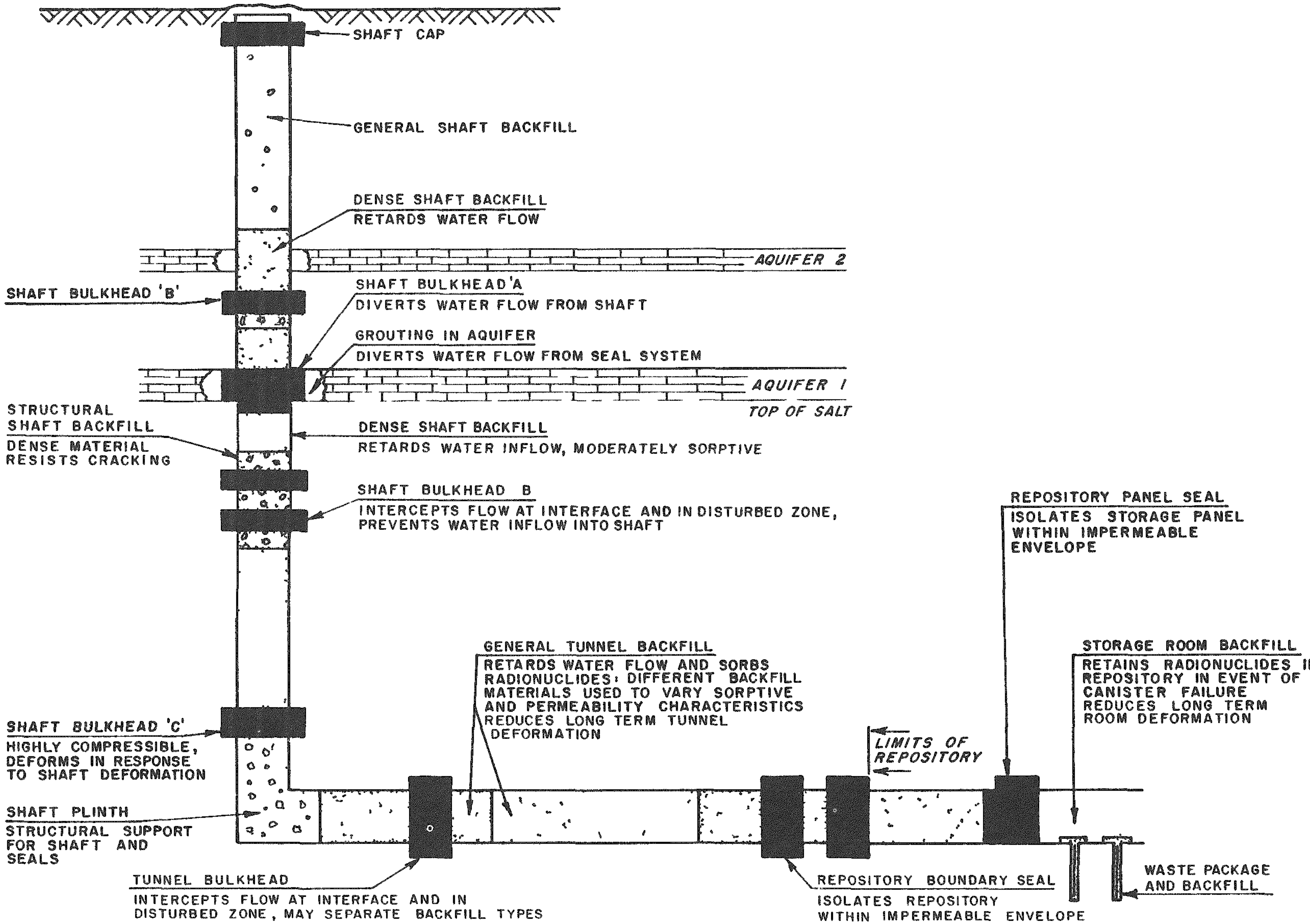

Figure 3-1. Basic Components for Shaft and Tunnel Seals in Salt

at full scale in order to demonstrate construction feasibility and performance.

Conceptually, bulkheads will be keyed into the walls of the shafts and tunnels in order to intersect the interface and part of the disturbed zone, and to provide additional shear resistance. In salt, the disturbed zone may consist of a destressed zone extending several radii from the shaft or tunnel wall in which permeability may be increased due to loosening of the crystal structure (Kelsall et al, 1982). In addition, blast-induced fractures may extend 1-2m from the wall. The preferred means to treat this disturbed zone is to take advantage of the ability of salt to heal fractures when subjected to confining stress. Appendix A discusses an analysis of the stress buildup around a relatively rigid, concrete bulkhead constructed in salt at 610m depth. For a seal at the base of the shaft (where there is no short-term temperature increase) the stresses in the disturbed zone will build to approximately 50% of the nominal lithostatic stress at the specified depth within a period of less than 10 years, and to 75% within 100 years. Stresses continue to build beyond this period but at a progressively slower rate. As described in Section 3.1.2.1, tests by Costin and Wawersik (1980) indicate that effective fracture healing should occur as the stresses build up. Additional analyses should be performed when detailed site specific geologic data are available to determine whether anomalous features such as clay seams or anhydrite beds above the roof of a tunnel could delay stress buildup.

Bulkheads that are keyed into the salt will further reduce disturbed zone and interface flow. Disturbed rock immediately adjacent to the shaft or tunnel wall will be removed and replaced with a denser material. Additional disturbance to the rock will be minimized by using low-energy excavation methods and by placing the seal material immediately following excavation. Interface flow will be reduced by interrupting the interface with the cutoff, and by the high normal stresses generated across the interface by creep of the salt against the more rigid bulkhead material.

Two main materials are considered for bulkheads, concrete, and salt in the form of pressed bricks. Concrete has been used extensively for bulkhead construction in mines and tunnels. It has the advantages of being relatively strong, impermeable, insoluble and inexpensive. In addition, a concrete bulkhead is fully effective as an internal seal within the penetration immediately following construction. Interface stresses can be developed by using an expansive concrete and, as noted above, stress within the disturbed zone should build to levels effective for fracture healing within a relatively short period (less than 100 years).

Pressed salt bricks have the advantage of being composed of the same material as the host rock. As the salt creeps, the joints between the bricks, and between the bricks and the penetration wall, should heal forming an homogeneous mass indistinguishable from undisturbed salt. The time for this process to occur should be determined by carefully controlled laboratory tests. For purposes of the schematic designs presented herein, preliminary analyses (Appendix A) have been conducted to estimate the period required for stresses within the bricks placed in a tunnel to build to lithostatic or to a level at which effective fracture healing should occur. Considering a tunnel adjacent to the base of the shaft where there is essentially no temperature rise, and an ideal case where the bricks completely fill the tunnel initially, the stresses within the bricks will approach 50% of the lithostatic stress within about 10 years and 75% within about 100 years. (For comparison, it will take about 1000 years to attain the 75% stress level in crushed salt placed in the same tunnel. Both analyses are for SENM salt.) For a case where an air gap of 0.3m is left between the bricks and the tunnel ceiling, the required period to achieve a specified stress level is increased by about 200 years. This period could be reduced by compacting crushed salt in the gap at the ceiling. Shorter periods for both closure and consolidation would be required for locations closer to the waste, or for a salt which creeps faster than the SENM salt. Collectively, these analyses suggest that salt bricks can be used to form bulkheads which will become effective more quickly than crushed salt but less quickly than concrete. Salt bricks should not be considered for the shafts where insoluble materials are required.

3.1.3.2 Backfills

It has been noted previously that the functions for backfills are to retard ground water flow and radionuclide migration, and to limit long-term deformation of the rock mass. The primary candidate materials for backfill are crushed salt and less soluble clay-bearing materials. In general, crushed salt will be used both in the repository and in access tunnels where in situ stresses and temperatures due to waste decay are both relatively high. These conditions are expected to promote relatively rapid consolidation and recrystallization. Earthen backfills will be used in the shafts where insoluble materials are required, and in sections of the tunnels close to the shafts, where temperatures may not be high enough to promote rapid consolidation.

It has been argued in Section 3.1.1 that there will be little incentive for storage room backfill to be sorptive provided that testing can conclusively demonstrate the consolidation and recrystallization of crushed salt. An element of redundancy may be provided in the system by enclosing the waste package in a clay-rich backfill and by extending the clay-rich backfill out of the emplacement hole onto the floor of the room. A major purpose of this backfill would be to form an essentially impermeable (and also sorptive) seal which would be effective immediately on emplacement, prior to the full consolidation of the salt. This would protect the waste package from any water excluded from the salt by either consolidation or brine migration. For this purpose sodium bentonite may be a suitable backfill material. This clay would swell on contact with water and form a tight interface against the salt. Sodium bentonite is also highly sorptive and it would help to retard radionuclide migration in the event of a package failure. Conceptually, the clay backfill above adjacent packages would not overlap so that a continuous double interface between salt and clay, which could be a pathway for water, would not be created along the floor of the room.

3.2 SHAFT AND TUNNEL SEAL DESIGNS

3.2.1 General Description

The general seal system described in Section 3.1.3 is readily applied to the WIPP site taking into account the site-specific stratigraphy and the geometry of the NWTSR-2 repository (Figure 3-2). The major features of the stratigraphy are the two known water-bearing dolomites within the Rustler Formation and the potential water-bearing zone at the Rustler-Salado contact. Primary sealing locations in the shafts thus occur at, and immediately below, the Rustler-Salado contact, and between the Rustler-Salado contact and the lower of the two dolomites, the Culebra. Other important seal locations in the shafts occur between the two dolomites and close to the bottom of the shafts. In all of these cases, the seals must be constructed so as to prevent seepage of water along the interface between the seals and the host rock or through the disturbed zone. The major components in the seal system are summarized in Table 3-2 and discussed in more detail in the following sections.

3.2.2 Tunnel Seals

Tunnel seals include the following components:

- Repository (storage room) backfill
- Repository panel bulkheads
- Repository boundary bulkheads
- Tunnel backfill
- Tunnel bulkheads

The locations of these components in the NWTSR-2 repository layout are shown in Figure 3-3.

3.2.2.1 Repository Room Backfill

Section 3.1.3.2 discusses why storage room and general tunnel backfill should be composed mostly, if not entirely, of crushed salt. In the present design only salt is used for the main tunnel backfill. As an additional precaution, it is proposed that a clay-rich material similar to the waste package backfill should be placed in a small mound over each emplacement hole. It is proposed that the backfill could be placed using conventional earth-moving equipment such as load-haul-dump

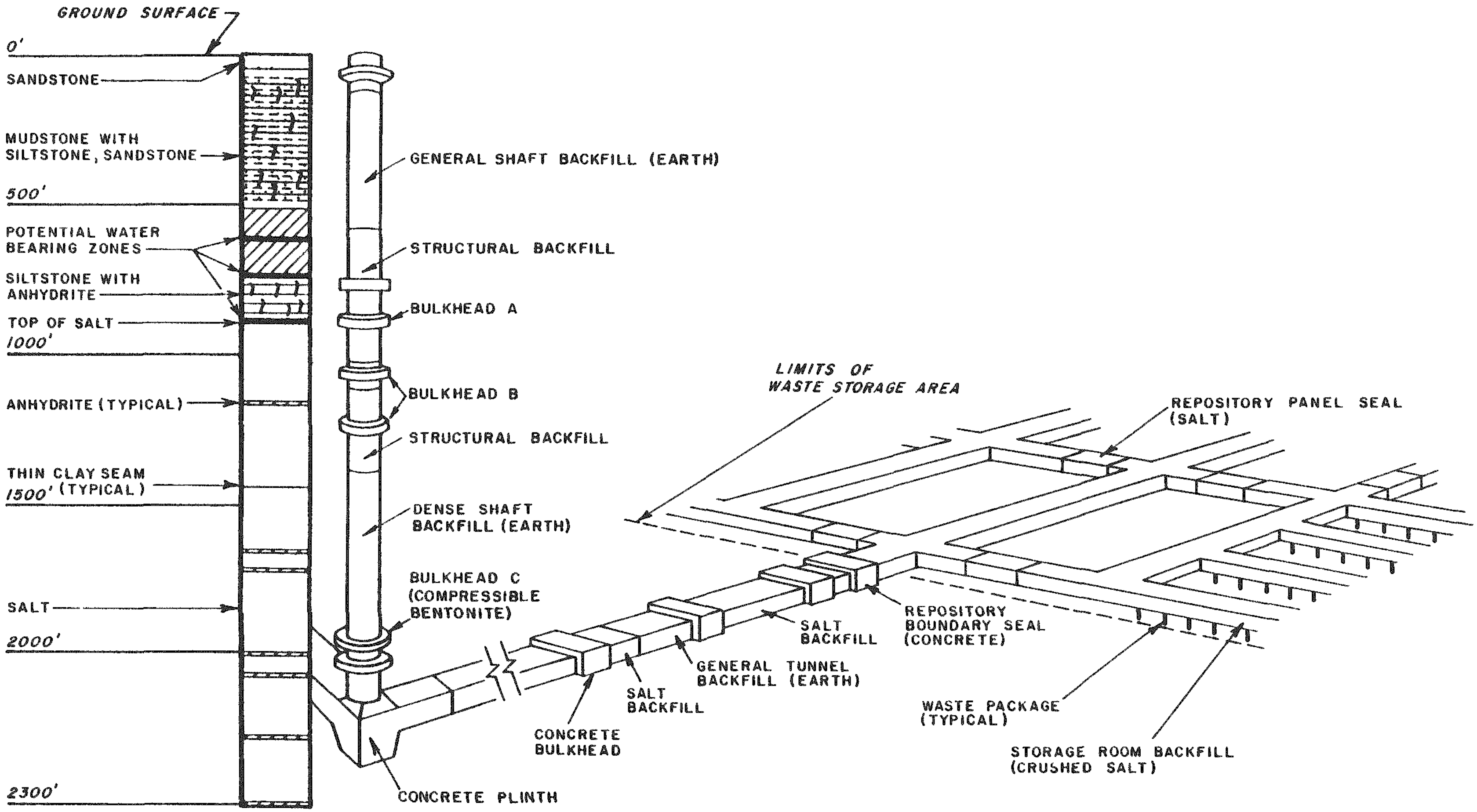

Figure 3-2. Tunnel-Shaft Seal System Schematic - Repository in Bedded Salt

Table 3-2. Basic Components in a Shaft and Tunnel Seal System for a Repository in Salt

SEAL COMPONENT	LOCATION	PRINCIPAL FUNCTION(S)	CANDIDATE MATERIALS
Storage Room Backfill	Waste storage rooms	Impermeable; prevents excessive long term rock mass deformation	Crushed salt
Repository Panel Bulkheads	Main access tunnel intersections	Impermeable barrier isolating individual storage panel	Salt Bricks or Highly compacted crushed salt or Concrete
Repository Boundary Bulkheads	Main access tunnels outside repository limits	Impermeable barrier isolating repository from shaft-access tunnel system	Concrete
Tunnel Backfill	Tunnels within repository and access tunnels connecting to shafts	Impermeable; sorptive; prevents excessive long-term rock mass deformation	Crushed salt; earthfill with special sorbers used in sections
Tunnel Bulkheads	Intervals in tunnels joining shafts and repository	Intersect interface and disturbed zone	Concrete
Shaft Plinth	Base of shaft(s)	Structural support	Concrete
Dense Shaft Backfill	Intervals in shaft (excluding bulkheads and structural backfill sections)	Retards ground water flow and radionuclide migration	Gravel-sand-clay mix highly compacted
Structural Shaft Backfill	Intervals in shaft adjacent to bulkheads	Impermeable; structural support for bulkheads	Concrete or grouted rockfill
Shaft Bulkhead "A"	Opposite lowermost aquifer (may be repeated in aquifer above)	Impermeable - prevents water infiltration from aquifer into shaft	Concrete and clay components with appropriate grout in host rock
Shaft Bulkhead "B"	Intervals in shaft between base and lowermost aquifer and between aquifers in shaft	Intersect interface and disturbed zone	Concrete with clay components
Shaft Bulkhead "C"	Close to base of shaft	Impermeable and deformable (responds to shaft deformation without cracking)	Compressible clay (possibly bentonite)
General Shaft Backfill	Above key aquifer(s)	General fill	Gravel-sand-clay mix
Shaft Cap	Top of shafts	Prevent access and surface water infiltration	Concrete

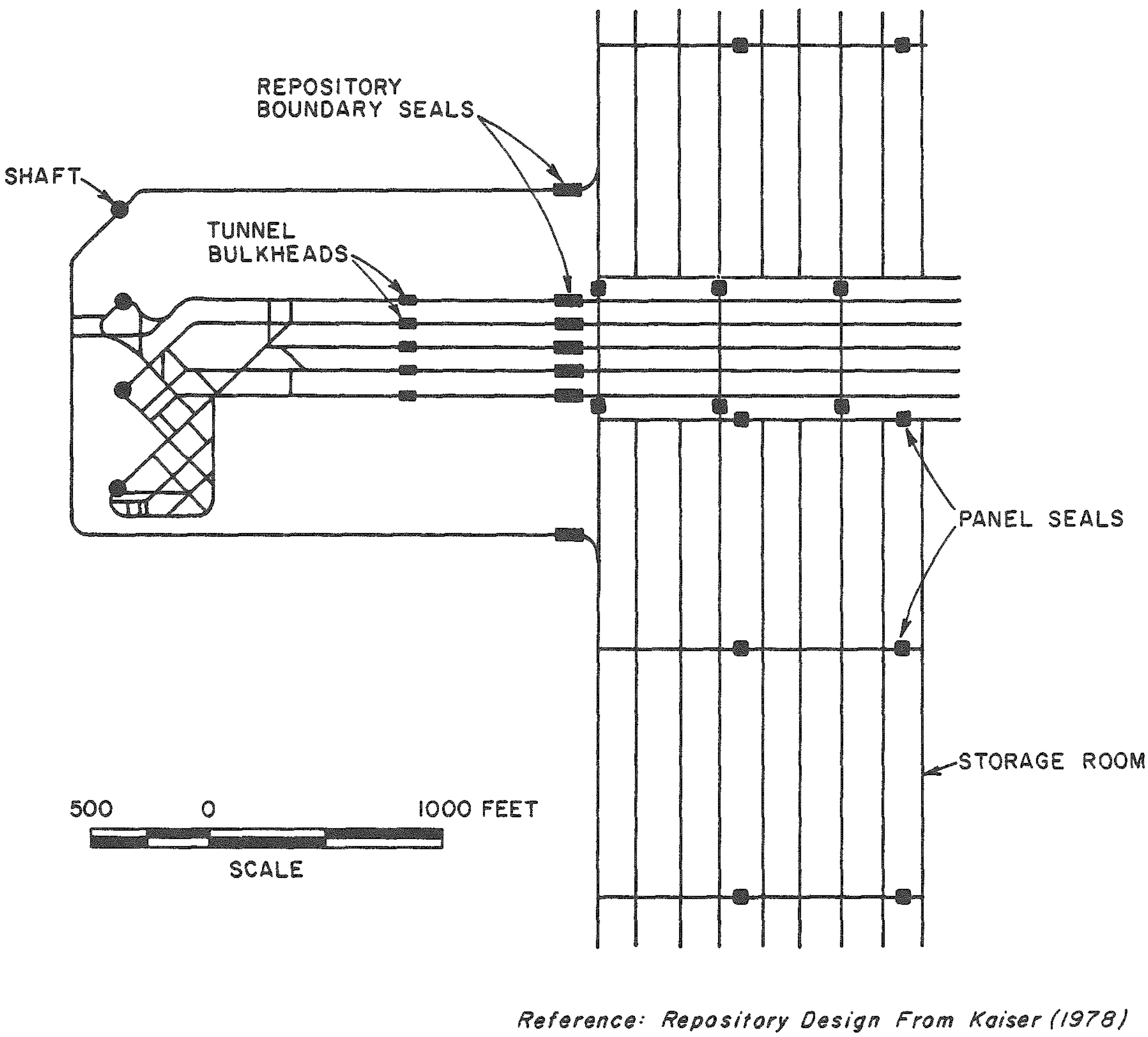

Figure 3-3. Tunnel Seals Schematic Layout - NWTSR-2 Repository

vehicles, bulldozers, and rollers. Close to the roofs of tunnels the salt could be placed pneumatically.

3.2.2.2 Repository Panel Bulkheads

Panel bulkheads are placed to isolate individual storage panels within the repository. In the schematic design, panel bulkheads are built from pre-formed salt bricks. Construction would first involve excavating a continuous keyway 1 to 2m deep around the complete tunnel perimeter in order to remove blast-damaged, stress-relieved, or weathered salt. The depth of the keyway should be determined on a site-specific or even location-specific basis. For example, the keyway should extend in the roof and floor to intercept any clay seams that could form a preferred pathway around the seal. Salt bricks would be stacked within the bulkhead area and any spaces between the bricks and the tunnel walls would be packed with crushed salt. It may be advantageous to wet the surfaces of the bricks in order to facilitate recrystallization.

The use of salt bricks rather than crushed salt is proposed in order to hasten the process of consolidation and recrystallization. Laboratory and field testing is required to demonstrate that salt bricks are effective and that they present a significant advantage compared with densely compacted, crushed salt. In the event (considered unlikely) that salt bricks are found to be ineffective, concrete bulkheads, as described below, could be used as panel seals.

As illustrated by Figure 3-3, the continuous cross-cuts employed in the NWTSR-2 repository necessitate the use of a large number of panel bulkheads in order to divide the repository into a series of separate storage panels. In future repository design development it may be desirable to use a layout that can be divided into separate panels with fewer bulkheads.

3.2.2.3 Repository Boundary Bulkheads

Repository boundary bulkheads are placed in the access tunnels connecting to the shafts, immediately beyond the limits of the repository (Figure 3-3). Their function is to form a low permeability envelope around the repository. The permeability of the boundary bulkheads should equal, or approach that of the undisturbed salt, and the bulkheads should be designed to eliminate flow in the disturbed zone. Concrete bulkheads, keyed into the salt, are proposed for this purpose. As discussed above for panel bulkheads, the depth of the keyway must be determined on a site-specific basis depending on the depth of disturbed salt and the presence of clay seams. The length of each bulkhead must be sufficient to create a zone in the midlength where there is little or no shear stress at the concrete-salt interface. Preliminary analyses indicate that the length should be at least twice the tunnel diameter.

The keyways should be excavated using a road-header type boring machine immediately prior to pouring the concrete. Boring machines produce a grooved surface which should be advantageous to reduce interface flow. As shown conceptually in Figure 3-4, provision must be made for air and bleed-water to escape during the concrete pour, and for grouting the interface. The grout used should be expansive in order to counteract any shrinkage in the main concrete pour.

For this application, concrete bulkheads are preferred to crushed salt and salt bricks (as proposed for the panel seals) in order to provide a cutoff in the disturbed zone effective in the short term. Additional work required in connection with concrete bulkheads includes characterization of the disturbed zone, detailed structural design, evaluation of concrete-salt interaction, evaluation of the need for construction in segments, and measurement of interface permeabilities.

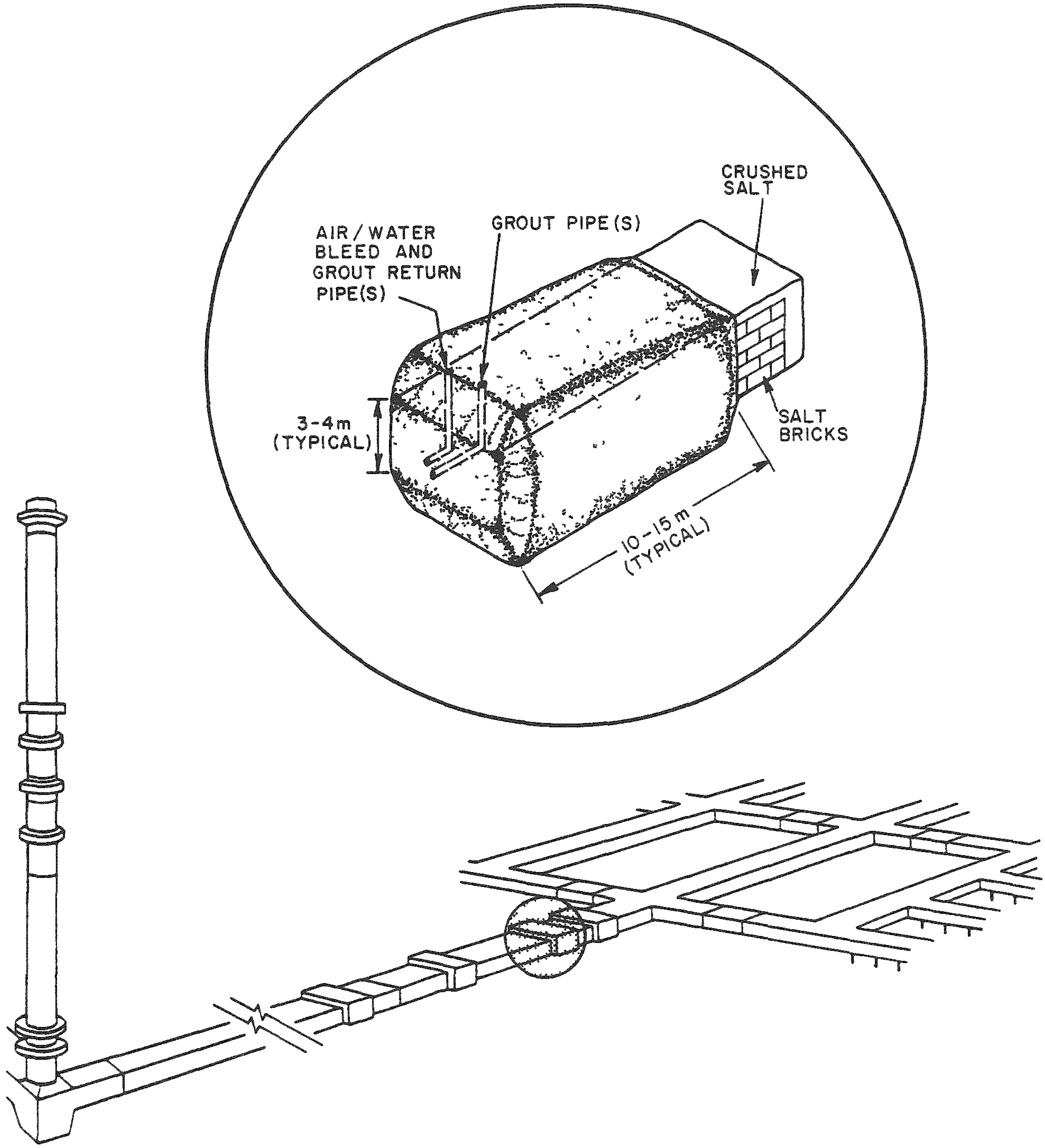

Figure 3-4. Concept for Concrete Tunnel Bulkheads - Salt Repository

3.2.2.4 Tunnel Bulkheads

High-density concrete bulkheads similar to those included in the boundary seals described above will be located at intervals in the access tunnels. Their primary function will be to cut off flow in the disturbed zone, but they may be used also to separate different types of fill. Design and construction methods will be the same as for the boundary seal bulkheads. Additional work required in connection with bulkheads includes characterization of the disturbed zone and modeling to evaluate how much of a cutoff and how many cutoffs might be required. Bulkheads composed of salt bricks might be considered if these are found to be highly effective.

3.2.2.5 Tunnel Backfill

Tunnel backfill is placed in all parts of the tunnels joining the shafts to the repository except where bulkheads are located. Two types of backfill are proposed, an earth-fill placed mostly near the shafts, and crushed salt placed near the repository. Earth-fill is proposed because it is effectively insoluble and because it can be engineered to have low permeability. A possible material would be a gravel-sand-clay mix with limestone or dolomite aggregate and 20-40% bentonite. Such a mix would probably have a hydraulic conductivity in the range of 10^{-8} to 10^{-12} cm/sec. An advantage of using bentonite is that it will swell on contact with water thus further reducing permeability. Bentonite is also sorptive. Additional work required in connection with tunnel backfill includes evaluation of the permeability of earth-fill as a function of composition, compaction and time, and performance of experiments to determine sorptive capacities of candidate materials under representative in situ conditions.

3.2.3 Shaft Seals

Shaft seals include the following components:

- 3 types of bulkhead, designated "A", "B", and "C"
- Structural backfill
- Dense backfill

- General backfill
- Shaft plinth
- Shaft cap

The locations of these components relative to the WIPP site stratigraphy are shown in Figure 3-5.

3.2.3.1 Bulkhead "A"

Bulkhead "A" is a relatively massive structure located at the lowermost potential water-bearing zone in the shaft (in the WIPP stratigraphy at the Rustler-Salado contact). Its function is to divert ground water flow away from the shaft at the contact with the aquifer and, accordingly, it is an important link in the overall seal system.

A key element of Bulkhead "A" (Figure 3-6) is enlargement of the shaft at the contact zone and the construction of a specially-formed concrete cylinder to deflect horizontal flow away from the vicinity of the shaft. This cylinder will be backfilled with a low-permeability clay laid on top of the salt and well-compacted. A clay mix which has a mild swelling capability might be used in this zone. On contact with water or brine, this material would swell and further reduce the permeability, but the swelling pressure would not be so high as to endanger the bulkhead structure. The dense clay fill is extended in the shaft above and below the bulkhead proper. Type B bulkheads (see below) are placed above and below the type A bulkhead in order to retard vertical ground water migration in the shaft.

Depending on the rock conditions encountered in each shaft, the contact zone adjacent to the shaft may be grouted prior to constructing the bulkhead. Grouting will not be considered if the contact zone is unfractured and non-porous. If the contact zone is fractured or porous, extensive grouting may be necessary in order to form a zone extending well beyond the excavation for the bulkhead from which water flow will be largely excluded. Disturbance to the rock mass by excavation of the bulkhead zone will be minimized by the pre-grouting and by carefully sequencing the excavation and applying temporary support as necessary.

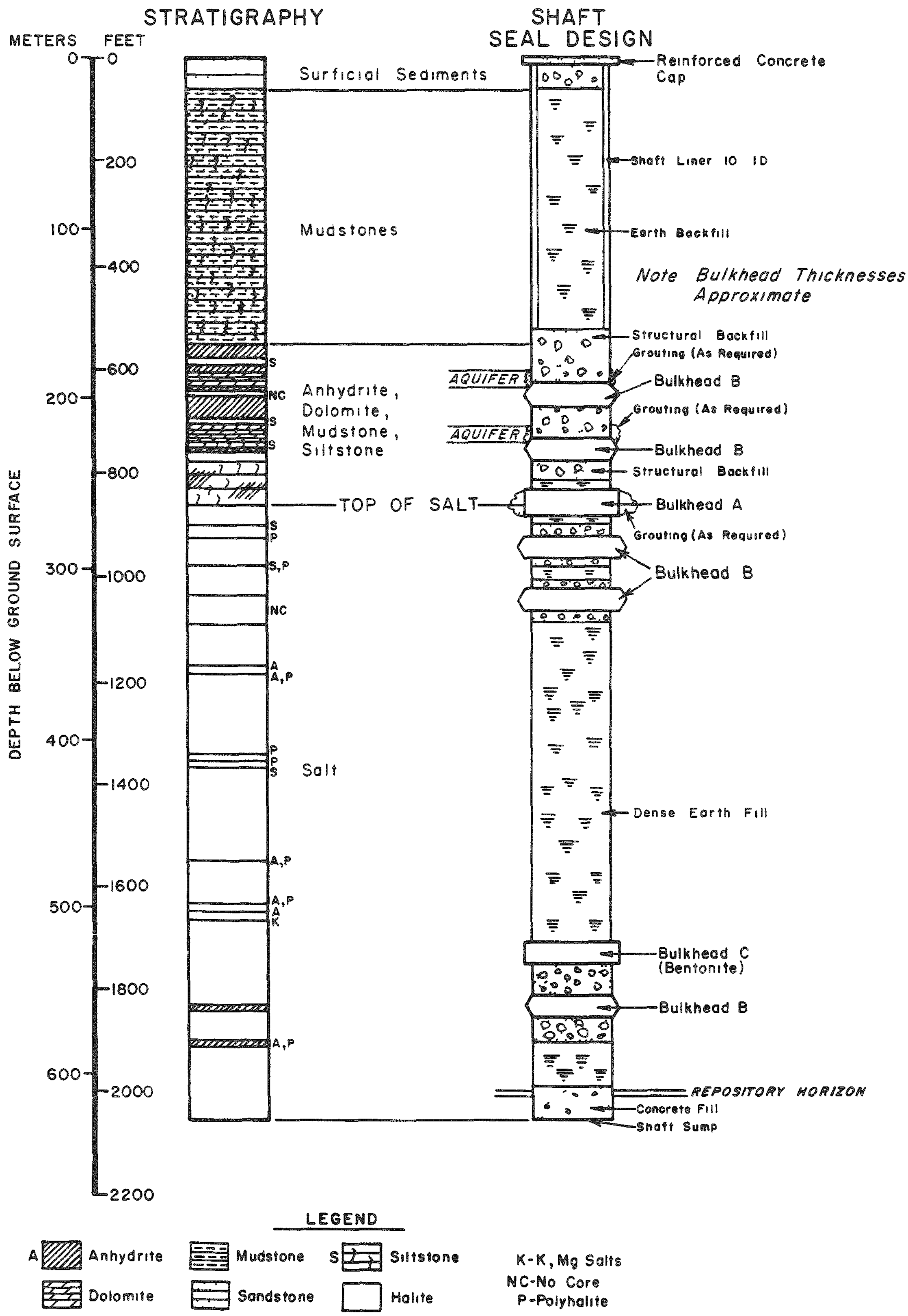

Figure 3-5. Schematic Layout for Shaft Seals in Bedded Salt

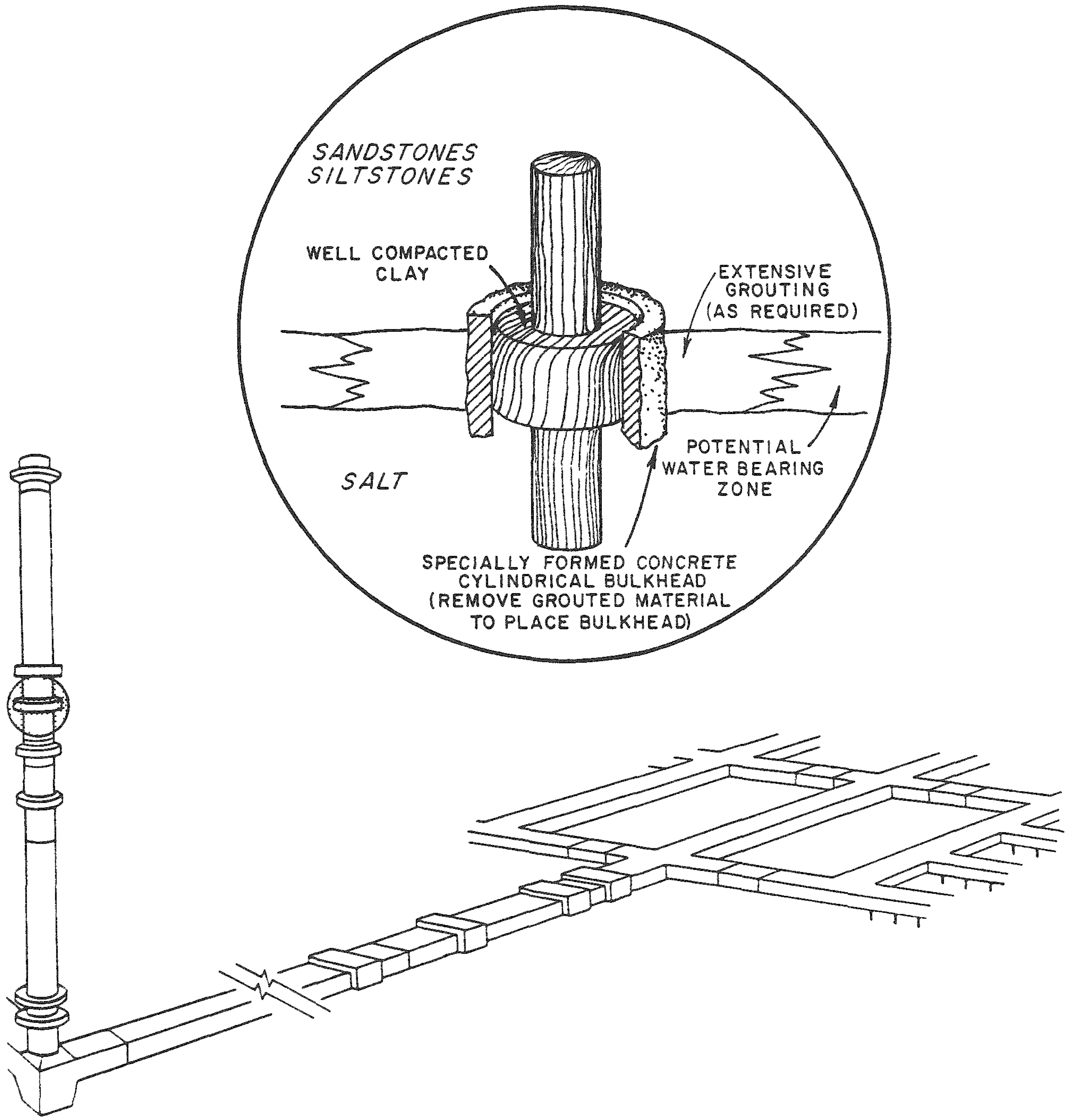

Figure 3-6. Type "A" Bulkhead at top of Salt

Additional work required in connection with Bulkhead "A" includes evaluation of suitable clay and grout materials and further consideration of construction methods. It is noted that final design and choice of construction methods must be reviewed on the basis of conditions encountered in the shafts.

3.2.3.2 Bulkhead "B"

Bulkhead "B" is a dense, impermeable structure keyed into the walls of the shaft and intended to prevent water flow through the disturbed zone and at the seal-host rock interface. As shown by Figure 3-5, bulkheads of this type will be placed between the Magenta and Culebra aquifers, immediately below the Culebra aquifer, at the bottom of the shaft, and possibly at other locations in the shaft as a backup to the seals at the top of the salt. It is anticipated that locations will be finalized according to conditions encountered in the shafts. Generally, bulkheads might be located both in salt sections, where creep will increase the stresses acting across the rock-bulkhead interface, and in relatively impermeable and insoluble zones such as anhydrite beds.

Figure 3-7 shows the general shape of the type "B" bulkheads with a double key excavated by machine or by hand. The major portion of the bulkheads must be composed of a low permeability material which bonds to the host rock, is stable, and leaves no connected void internally or at the seal/rock interface. A slightly expansive concrete is planned for this material. Layers of compacted clay are located between the three concrete segments to avoid the potential for continuous crack formation through the system due to temperature changes or structural deformation. This also permits the bulkhead to be more flexible to deformation from outside disturbances. A mildly swelling clay may be used for a portion or all of the clay component in order that the clay layers will act as gaskets by expanding on contact with water or brine. An alternative design might employ swelling clay in the central cutoff. Polymers

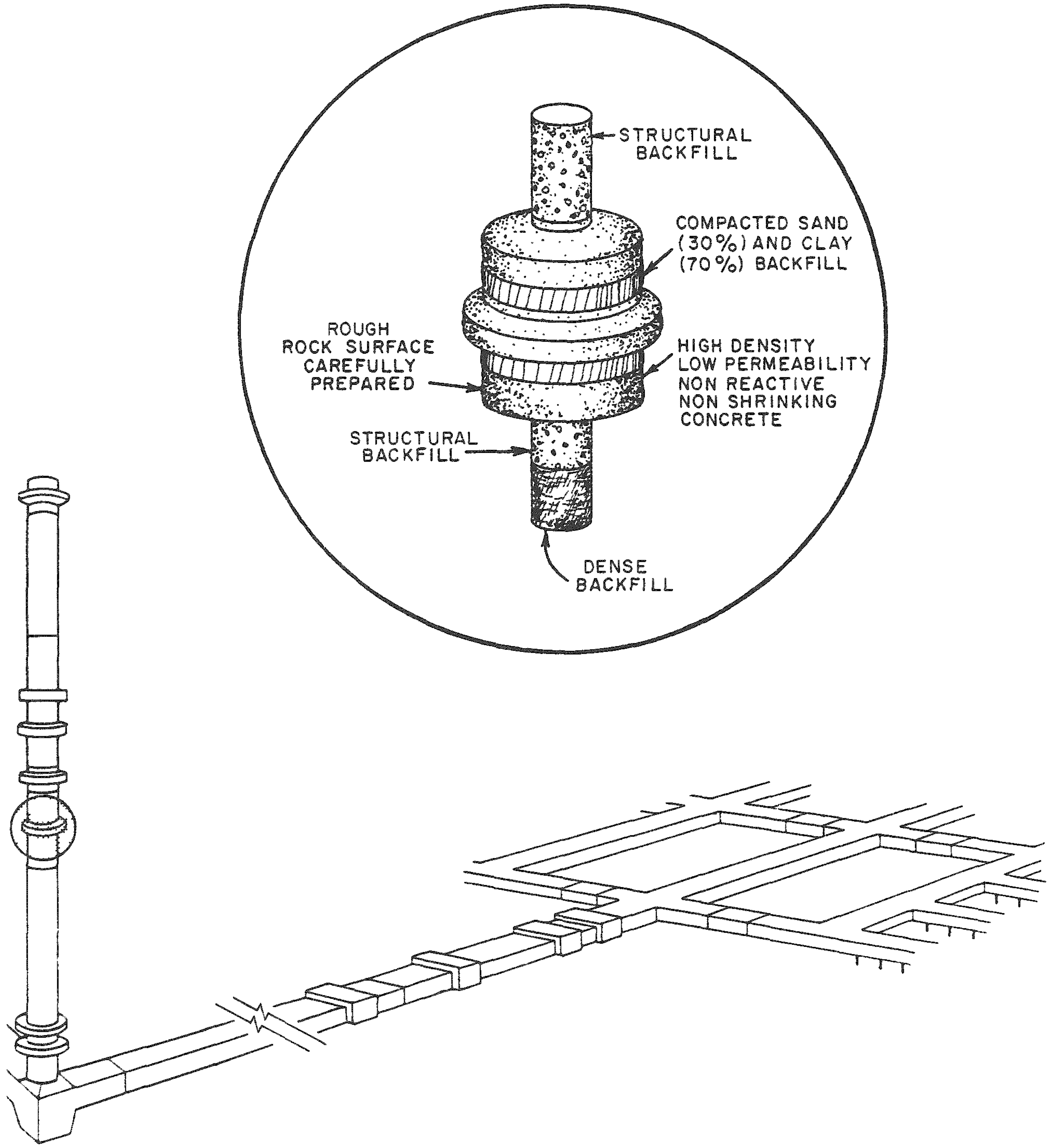

Figure 3-7. Type "B" Shaft Bulkhead

which expand on contact with water might also be considered for this purpose. Polymers have been used successfully for sealing behind mine shafts in salt (D'Appolonia, 1981), but their long-term stability is unproven. A dense structural backfill (Section 3.2.3.4) is located immediately above and below each bulkhead. This is included to absorb or deflect stresses away from the bulkhead proper.

Additional work required in connection with type "B" bulkheads includes characterization of the disturbed zone, modeling to determine the extent of the cutoff and number of cutoffs required, structural analysis of the composite concrete-clay structure, and evaluation of construction and placement techniques to minimize interface permeability and additional host rock disturbance. The major function of the bulkheads is to obtain the lowest possible interface permeability.

3.2.3.3 Bulkhead "C"

Figure 3-5 shows an additional bulkhead near the bottom of the shaft composed of highly compacted bentonite. This bulkhead will act as an additional water seal at the base of the shaft. Sodium bentonite is selected because of its low permeability, because it will swell and tend to be self-sealing when wetted, because it is compressible and will respond to slumping of the overlying seal materials or deformation of the shaft walls, and because it is expected to be durable in a salt environment. An added feature is that this component will be composed of a different material than the Type "B" bulkheads thus adding a degree of redundancy in the system. A bulkhead is located near the bottom of the shaft because it is anticipated that the salt at this level will be less fractured than at the top of the salt. In addition, this location is the last place to prevent either downward-percolating water from moving toward the repository or waste-contaminated water from migrating up the shaft. Additional work is required to confirm that bentonite will be stable in the anticipated placement environment.

3.2.3.4 Structural Backfill

As shown in Figure 3-7, sections of structural backfill are placed in the shafts above and below each of the bulkheads. This backfill is intended as a high density, low permeability material that is placed with a low water content in order to minimize dehydration effects. The functions of the backfill are to provide a low interface permeability and to deflect bearing stresses away from the bulkheads and the important cutoff collars.

Conceptually, the structural backfill will consist of a dense concrete, possibly emplaced by grouting pre-placed aggregate. The aggregate will consist of cobble (approx. 100mm) and gravel-size fragments of dense rock. As a result of pre-placing the aggregate, the rock fragments will be in grain-to-grain contact. After emplacement, the rock fill will be grouted through removable pre-placed pipes and tamped or vibrated to yield a dense plug of high strength and low permeability. A Class H cement is presently being considered for use in conjunction with locally derived aggregate. Preferably, the aggregate chosen will be one that has a demonstrated compatibility with the site ground water.

Additional work required in relation to the structural fill includes structural and thermal analyses of the bulkheads and adjacent fill sections to determine more precisely material requirements. These analyses should compare the advantages and disadvantages of the grouted rock fill and a more conventional poured concrete.

3.2.3.5 Dense Shaft Backfill

The remaining sections of the shafts in the Rustler and Salado, between the bulkheads and the structural backfill sections, will be filled with a highly compacted earth backfill. This may be a sand and gravel mix with a large clay component included to reduce permeability and increase sorption. "Natural" materials similar in composition to materials found in the stratigraphy will be chosen in order to assure longevity.

3.2.3.6 General Shaft Backfill

Above the Rustler Formation, the shafts will be filled with a general backfill. This may be an earthen material similar to the dense fill used lower in the shafts but with less stringent requirements for low permeability. Further consideration must be given to whether it is necessary to remove the shaft lining in this section.

3.2.3.7 Shaft Plinth and Cap

The bottoms of each of the shafts and the entrances to the adjacent tunnels will be filled with concrete intended to limit differential movement of the plug materials and the shaft walls which could cause cracking and shearing at the seal-rock interface. This concrete may require incorporation of some earth-type materials if detailed stress analyses show that the concrete rigidity should be reduced to avoid any undesirable "rigid body" effects of the block within the salt mass. Each shaft will be capped with a reinforced concrete bulkhead which will prevent surface drainage into the shaft and provide a permanent marker of the shaft location.

3.3 BOREHOLE SEALS

3.3.1 General Considerations

3.3.1.1 Significance of Borehole Plugging

Although in previous years a significant proportion of the repository sealing program effort has been devoted to borehole plugging, greater emphasis is now being given to shaft and tunnel sealing. Two reasons exist for this change of emphasis. First, considering that flow through a penetration is proportional to area, it is apparent that a shaft constitutes a much more significant potential flow pathway than a borehole. Second, with prudent repository siting and exploration practices, there should be few, if any, boreholes connecting the ground surface and the repository that are not coincident with a shaft location or contained within a pillar of undisturbed rock.

Borehole plugging may assume greater significance in two cases, where a borehole penetrates the buffer zone of undisturbed rock provided around the repository, or where a borehole provides communication between two aquifers or between an aquifer and the host rock. An example of the first case might be an old oil well at a salt dome site which penetrates through the salt in the buffer zone around the repository. This borehole will not endanger repository security, and it should not be a licensing concern, if there is a demonstrated technology for sealing boreholes. An example of the second case is where a borehole at a salt site penetrates through a fresh-water aquifer into the salt. This is a particular concern where the contact between the salt and the overlying caprock or sediments is permeable and could act as a locus for salt dissolution.

3.3.1.2 Borehole Siting

The necessity for borehole plugging may be at least partly avoided by prudent borehole siting. Three examples of how problems may be avoided are discussed below.

Exploration Boreholes

A current exploration approach, which is supported by the NRC in 10CFR60 (USNRC, 1981), is that exploratory boreholes should (if possible) be drilled at future shaft locations in order that the boreholes are consumed by shaft excavation. This is a laudable policy provided that the borehole does not deviate outside the limits of the shaft excavation. Should this occur, the borehole may cause a problem in shaft sealing by providing a potential pathway for flow immediately adjacent to the shaft.

Figure 3-8 shows the deviation of the borehole ERDA-9 at the WIPP site in relation to the cross-section of a 15-foot diameter shaft which is proposed at the borehole location. If the shaft center-line is located exactly at the borehole location, the borehole will deviate from the shaft in the Rustler Formation and will form an obvious potential bypass around the shaft seal. This potential problem can be largely avoided by moving the shaft center-line approximately 10 feet to the west.

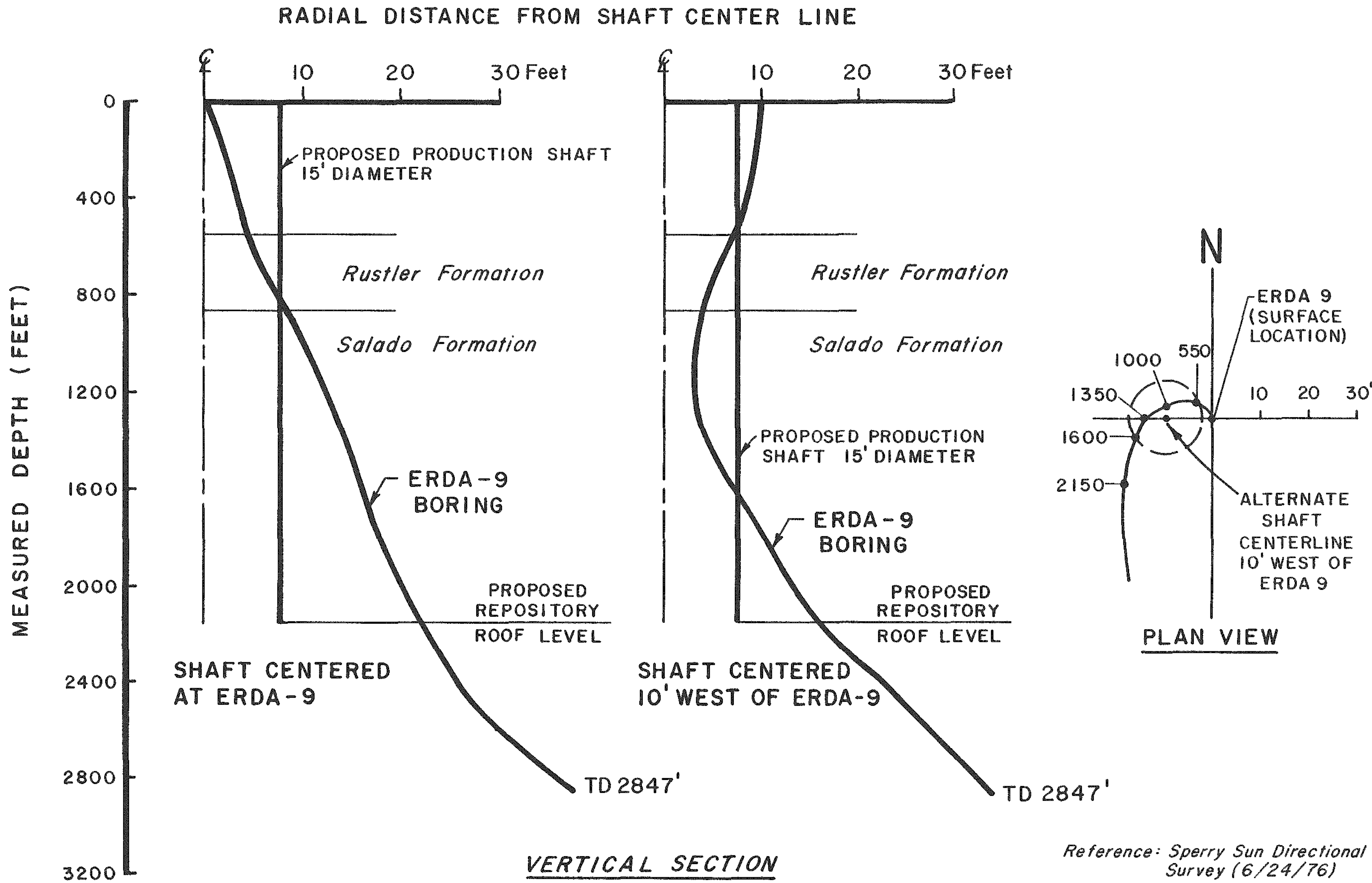

Figure 3-8. ERDA-9 Borehole Deviation in Relation to Proposed Production Shaft Excavation Volume - WIPP Site

A further point regarding borehole siting, not directly related to sealing, concerns the relative locations of boreholes within the repository area. In all current repository designs, the shafts are located close together within an isolated shaft pillar. If boreholes are drilled only at shaft locations, it follows that information will be obtained from only a limited part of the repository area. A preferable scheme might be to spread the boreholes over the repository area with each borehole protected by a pillar of undisturbed rock. A borehole should be drilled at one of the shaft locations, as a stratigraphic pilot bore, maintaining very close vertical control.

Boreholes Supporting Shaft Construction

At a salt site (particularly a salt dome) shaft construction may require pre-grouting or freezing to penetrate aquifers above the salt. If either freezing or grouting is used, it is essential to avoid continuous boreholes which penetrate through aquifers to the top of salt (D'Appolonia, 1981). If freezing is used, there is no necessity for the freeze pipes to penetrate the salt. If grouting is used, each aquifer or zone requiring grouting should be treated individually by drilling from the bottom of the shaft after each water-bearing zone has been penetrated.

Horizontal Boreholes

Plans for early shaft exploration and test facilities may consider horizontal or inclined boreholes drilled from the shaft bottom or from the test drifts. Such holes could be required to demonstrate the continuity of the repository formation and to investigate vertical fractures in the rock mass. As discussed in Section 3.3.3, there is no demonstrated technology for sealing long horizontal holes, but this is not a concern if the holes do not penetrate significantly outside the proposed area of excavation. A strong recommendation of this report is that horizontal holes should not be used for exploration within the buffer zone around the repository. If it is required that horizontal holes be drilled into the buffer zone, it is proposed that they should not penetrate to greater than 10 to 20 percent into the width of buffer zone beyond the repository boundary.

3.3.1.3 Requirements for Sealing

At each site, criteria must be developed for distinguishing boreholes which must be sealed according to stringent specifications developed by the repository sealing program from boreholes which can be sealed according to less stringent standards. State standards for sealing oil wells might be applied to boreholes which do not pose a threat to repository security. As a general rule, any borehole within the buffer zone established around the repository should probably be sealed according to sealing program standards. Boreholes may be evaluated on an individual basis according to the distance from the repository and the strata (especially aquifers) penetrated.

3.3.2 Plugging Designs for Vertical Boreholes

The sealing procedures for boreholes may vary considerably from hole to hole depending (as noted above) on the location and depth of the hole, and also on the condition of the hole. A major consideration may be the presence and condition of casing. Plugging a hole without removal of casing would produce a double interface which could be a significant preferred flow path particularly in the long-term as the casing or grout behind the casing deteriorated. Casing need not be a concern if there is sufficient open hole above the repository depth in which to form an adequate plug. A preliminary estimate is that 100m of open hole should be sufficient for this purpose. At shallower depths it may be necessary to perforate the casing to grout in sections where logging indicates a poor cement bond, or in sections where it is important to maintain a good seal between water-bearing zones. Any hole which is fully cased to a depth below the repository should be evaluated on an individual basis. In practice, it is unlikely that such a hole would be located in a critical location. Presumably a barrier pillar would be left between the repository and any old borehole close to the site, and repository exploratory holes would not be cased at repository depth.

Special consideration must be given to a borehole located close to a shaft. As discussed above, it is preferable that exploratory holes drilled to support shaft construction should be located so as to be consumed by shaft excavation. If a hole is to be drilled adjacent to the shaft location, future sealing will be greatly facilitated if the hole is not cased in the salt and at the top of the salt. Casing installed at the top of salt in a hole located close to a shaft would have to be removed prior to sealing in order to ensure that the hole could not transmit unsaturated water to the salt interface.

Figure 3-9 shows a schematic method for sealing a vertical borehole drilled from the ground surface. The borehole would be sealed in stages:

(i) Characterize the hole by examining drilling records and, if necessary, by running additional logs. Particular attention is paid to identifying permeable zones and to describing the hole geometry using caliper logs and downhole television.

(ii) Perform packer tests to identify permeable zones.

(iii) Flush the hole to remove debris and clean the surface with brushes or reamers.

(iv) Squeeze grout with cement in the more permeable zones, as appropriate.

(v) Drill out the hole and repeat packer tests in permeable zones; repeat the squeeze grouting if necessary.

(vi) Drill out the hole and grout with bentonite or chemical grout (as necessary, if cement grouting does not eliminate water losses).

(vii) Drill out the hole and part fill from the bottom with an expansive cement (See Figure 3-9).

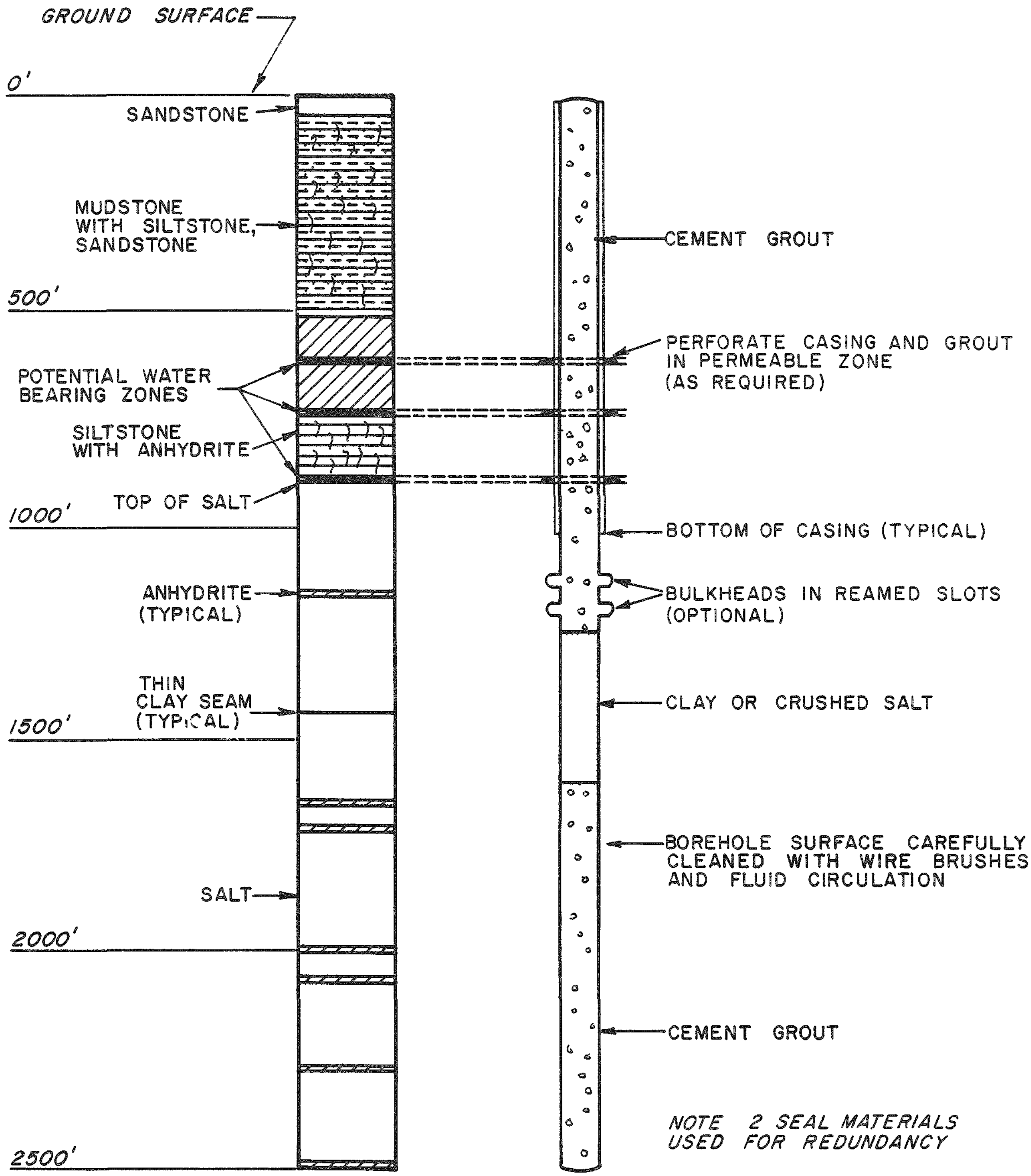

Figure 3-9. Schematic Design for Sealing Vertical Borehole in Salt

(viii) Fill section of hole above first cement stage with crushed salt or clay, densely-compacted in place.

(ix) Fill remaining section of hole to ground surface with expansive cement.

These procedures are those that would be used in open sections of the hole. At shallower depths, it should be sufficient to perforate the casing and squeeze grout in water-bearing sections.

Conceptually, two plugging materials will be used. The primary candidate at present is a cement grout similar to BCT-IFF. Cements placed in a slurry can penetrate irregularities in the hole and are preferred over materials which require in-hole compaction. An alternative to BCT-IFF might be a grout which offers greater deformability and resistance to cracking. The second plugging material might be crushed salt (placed towards the bottom of the hole) or clay compacted in place. Particularly valuable information regarding the comparative performance of seal materials will be obtained from the borehole simulation tests being conducted by Terra Tek (Lingle et al, 1981). Cutoffs, included in the seal below the lowermost water-bearing zone to intercept interface flow, could be created using an under-reamer. Laboratory tests should be conducted to evaluate the effectiveness of cutoffs.

3.3.3 Sealing Horizontal Holes

Sealing long horizontal holes is likely to be a more complex problem than sealing vertical holes. In vertical holes, gravity settling of seal materials acts in favor of sealing by forcing materials into irregularities in the borehole wall. Conversely, in horizontal holes gravity settling may result in separation of the seal away from the roof of the hole. Sealing problems may be particularly severe in very long holes in which deviation of the hole can result in high points in which pockets of air or bleed-water may be trapped. Also, there is a much greater chance that tools used for drilling, cleaning, or placing seal materials in horizontal holes can become stuck and difficult to remove.

Valuable experience with grouting long horizontal holes has been gained by the U.S. Bureau of Mines with regard to sealing methane drainage holes in coal mines. Aul & Cervik (1979) describe the grouting of six holes ranging in length from 140 to 650m using a flyash cement. The procedure was to insert a schedule-40 PVC pipe to the back of the hole. Grout was injected into the PVC pipe and returned along the annulus. An interesting aspect of this work is that some of the grouted holes were later intercepted at several locations by mining. This showed that the holes were not properly sealed at all locations. In some cases, grout was found partly filling the hole. In one case, there was no grout in the hole even though the same hole was found to be completely sealed at greater depths. Generally it was found that the front parts of the holes were sealed better, even though the holes were grouted from the back.

This case history is included as illustration that further attention must be given to methods for sealing horizontal holes. Field trials should be conducted in in situ test facilities where it is possible to mine through the sealed holes to examine the continuity of the plugs. Regardless of developments in technology, however, it is important to note that there should be no necessity for creating a sealing problem with horizontal holes.

3.4 APPLICABILITY OF DESIGNS TO OTHER SALT SITES

The designs described in the previous sections have referred to the WIPP site stratigraphy and hydrology. To a large extent, however, the designs are generally applicable to any repository in salt. Seal functions will be the same at any salt site so that the same basic components (Figure 3-1, Table 3-2) will be required. Also, crushed salt will be a major seal and backfill component at any salt site. Similar cementitious materials can probably be used at different salt sites but earth-fill materials may be expected to vary from site to site with locally-derived materials used in each case.

The major difference that might be found among different sites would be the thickness of salt between the repository and the first overlying aquifer. At some sites (for example, the Paradox Basin), this interval may include interbeds that are not considered aquifers but which are relatively permeable. Another difference is that the first water-bearing zone above the salt may be much more permeable at some sites (for example, some salt domes) than at the WIPP site. Extensive grouting might be required in the permeable zone in order that the shaft liner can be removed at the top of the salt and replaced by a bulkhead.

4.0 FUTURE ACTIVITIES

The designs described in the previous chapter are working designs presented for review and intended to be modified according to performance assessment, data obtained from laboratory and field tests, and detailed design calculations. Major areas in which further work is required to improve the design are outlined in the following sections.

4.1 SITE CHARACTERISTICS

The design must be updated when a site for a commercial repository in salt has been selected and when detailed stratigraphic, hydrologic and geochemical data are available from shafts and tunnels excavated at the site. Information that is particularly required includes the nature of the top of salt and the overlying material, the presence or absence of fractures in the upper part of the salt (especially for salt domes), the location and characteristics of interbeds within the salt, and the nature of the disturbed zone around penetrations.

4.2 MATERIALS

Three candidate seal materials have been identified for a repository in bedded salt: cementitious materials, earth materials, and crushed salt. The major unresolved materials issues are as follows:

- Ability of crushed salt to anneal, and fractures in salt to heal, under repository pressure and temperature conditions.
- Interface permeabilities for all host rock-material combinations.
- Mix formulation and properties for a high creep low modulus concrete.
- Comparative performance in a salt environment of earth materials with swelling or non-swelling clay minerals, and chemical and thermal stability of clays, leading to designation of appropriate seal materials.

- Optimum composition and initial density for earth materials.
- Interaction between earth and cementitious materials if placed in adjacent seal components.
- Performance of all materials over time in response to changing or cyclic temperature, stress and moisture conditions.

4.3 ANALYSIS OF CRUSHED SALT CONSOLIDATION AND FRACTURE HEALING

Analyses presented in this report indicate that consolidation of crushed salt is an effective processs for sealing penetrations in salt. These analyses have been simplified, however, to examine only circular openings, and they have considered only a few locations in the seal system. They are also based on preliminary data regarding consolidation behavior. Additional analyses are required to:

- model actual room geometries
- account for more rigorously derived temperature histories for seal locations
- consider a greater number of seal locations within the repository as well as the shaft pillar
- account for site-specific salt characteristics
- incorporate results from further testing of crushed salt properties
- model stress changes around tunnel bulkheads taking into account clay seams, anhydrite beds or other anomalous features occurring in the roof of the tunnel

4.4 BACKFILL SORPTIVITY

In principle, the basic design goal of limiting radionuclide release may be achieved by installing seals of such low permeability that radionuclide release is limited solely by ground water flow rates and travel times. Further work is required to determine the extent to which seals should also be sorptive. This applies particularly to a repository in salt since crushed salt, which must be considered as a primary seal material, has a limited sorptive capacity. If seals are to be sorptive, it will be necessary to decide where in the system sorptive material should be added. For example, should the sorptive agents be mixed with the general backfill, or placed in separate sections? Further testing is required to determine sorption properties under anticipated repository conditions of (e.g., Eh, pH ground water composition).

4.5 EMPLACEMENT AND CONSTRUCTION TECHNIQUES

Although construction feasibility has been an important consideration in developing schematic designs, detailed step-by-step construction procedures are not presented. This is considered appropriate for a schematic design, in which seal materials are not precisely defined, provided that the basic materials used are in common use in engineering practice. Further attention must be paid to three specific areas:

- Emplacement methods for backfill in tunnels that will achieve adequate compaction near the roof and will not leave a void. This is not as great a concern in salt as in other rock types because creep closure will tend to close any voids at the roof and increase compaction throughout the backfill. Additional tests and analyses are required to predict how fast voids will close in salt.

- Construction methods for bulkheads. More detailed work is required to address factors such as the required expansivity of concrete bulkheads, the possible need for constructing bulkheads in segments, and the effects of heat of hydration. Detailed design should further evaluate the use of clay gaskets within concrete bulkheads.

- Emplacement methods for borehole plugs. Additional work, including laboratory tests and field trials, is needed to evaluate placement methods for boreholes. Attention should be given to compaction methods for clay materials in vertical holes and general methods for use in horizontal holes.

4.6 DESIGN OPTIMIZATION

In order to achieve the basic design goal of limiting radionuclide release, seal components must provide a number of separate functions, for example:

- limiting ground water inflow (or outflow)
- ensuring long ground water travel times
- limiting radionuclide migration by chemical or physical retardation
- limiting deformation of the host rock

In some cases functions may appear to be contradictory. For example, travel time may be increased by increasing system porosity but this may also increase flow rates. Parallel approaches are required in future performance assessment:

- Analysis of the existing design and evaluation of performance in terms of acceptable standards and sensitivity to variations in input parameters.
- Optimization of the design relative to a thorough evaluation of performance requirements.

The second approach will involve a large number of simplified parametric analyses to evaluate factors such as the relative positions of seal components, the optimum number of specific components (such as bulkheads), and the material properties of different components. Material properties to be evaluated should include permeability, porosity, sorptivity, and dispersivity.

4.7 FIELD TESTS

Field tests will be required to demonstrate emplacement techniques and to verify in situ seal performance. For the most part, field tests will be conducted in an underground test facility at a candidate repository site after conceptual seal designs have been completed (Section 1.2). Detailed field test plans should be developed as part of the conceptual designs.

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APPENDIX A

CONSOLIDATION BEHAVIOR OF CRUSHED SALT AND STRESS BUILD-UP ON BULKHEADS PLACED IN SALT

A.1 INTRODUCTION

A number of analyses have been conducted to determine the time required to consolidate crushed salt backfill to a density and porosity equivalent to that of undisturbed, intact salt under varying conditions of pressure and temperature. Elements of these analyses include:

- review of laboratory test data relating to:
  - consolidation characteristics of crushed salt
  - permeability of crushed salt as a function of porosity
  - strength of crushed salt as a function of porosity
- calculation of temperature histories following waste emplacement at specified seal locations (for spent fuel and commercial high-level waste)
- calculation of closure rates and cumulative closures for specified seal locations given specified temperature histories, stress levels, and salt characteristics
- analyses of consolidation behavior, considered as a function of time, salt characteristics, waste form, and initial porosity:
  - porosity/density
  - permeability
  - stresses within the backfill
  - strength

Additional analyses consider the stress changes around and within concrete or salt bulkheads emplaced in a shaft or tunnel in salt.

The analyses included herein are considered preliminary in that they are based on sparse laboratory test data and that they incorporate several simplifying assumptions. Although the results are encouraging in that they indicate that effective consolidation will occur within a relatively short period (400 to 1000 years depending on location), additional testing and analysis are required to add confidence to the results. Additional work is required in the following areas:

- Laboratory testing to better define consolidation behavior and permeability-porosity relationships for crushed salt.
- Modeling of actual room geometries (as opposed to idealized circular openings considered herein).
- Modeling of specific seal locations accounting for the proposed sequencing of excavation and waste emplacement (in the current analyses rooms are assumed to be backfilled immediately following waste emplacement).
- Modeling of site specific salt characteristics.

A.2 LABORATORY EVIDENCE OF CRUSHED SALT CONSOLIDATION AND FRACTURE HEALING

A.2.1 Crushed Salt Consolidation

Laboratory triaxial consolidation tests have been performed on cylindrical specimens (10cm diameter by 20cm length) of crushed salt from the Avery Island Mine, Louisiana, for hydrostatic stresses up to 13.8 MPa and temperatures from 29°C to 52°C (Wagner, 1980). The samples used were obtained at the crusher station on the 268m level of the mine. Approximately 70% of each sample was in the particle size range from 2.5. to 5mm, with 25% less than 2.5mm. The initial total porosity of the crushed material was about 41%. Quasi-static consolidation as well as creep consolidation data were obtained for time periods ranging from a few hours to about 13 days. Wagner also presents uniaxial consolidation data obtained for commercial grade (cattle) salt for stress levels up to 27.6 MPa and temperatures ranging from 21°C to 204°C. The data presented by Wagner are in general agreement with unpublished results from similar consolidation tests in progress at Sandia National Laboratories using crushed salt from the Carlsbad potash mining district in southeastern New Mexico.

Figure A-1 is a plot of total volumetric strain as a function of mean hydrostatic stress for quasi-static loading of Avery Island and commercial grade salt. The time invariant constitutive relationship for the dilatational components of stress and strain used to represent this data can be written as:

$$\sigma_m = A[\exp(Be_v) - 1] \qquad \text{(A-1)}$$

where σ_m is the mean hydrostatic stress, A and B are experimentally determined constants, and e_v is the total volumetric strain. By taking the derivative of the relationship for mean hydrostatic stress with respect to total volumetric strain, and considering that a constant value is achieved after full consolidation, the following functional relationships between the effective tangent bulk modulus and the total volumetric strain are obtained:

$$\begin{aligned} K_T &= AB\exp(Be_v) && \text{for } e_v < e_c \\ K_T &= K_I && \text{for } e_v \geq e_c \end{aligned} \qquad \text{(A-2)}$$

where K_T is the effective tangent bulk modulus, K_I is the bulk modulus of the intact salt, and e_c is the total volumetric strain at which intact properties are reached. Table A-1 gives the values of the constants used for the current work.

Table A-1. Values for Parameters in Quasi-Static Consolidation Law for Crushed Salt From Avery Island, Louisiana

Parameter	Value	Units
A	0.5116	MPa
B	18.734	mm^3/mm^3
e_c	0.41	mm^3/mm^3

These values were selected to yield a bulk modulus at a total volumetric strain of 41% corresponding to the bulk modulus for intact halite taken to be 20.7 GPa. As shown by Figure A-1, these values also give a

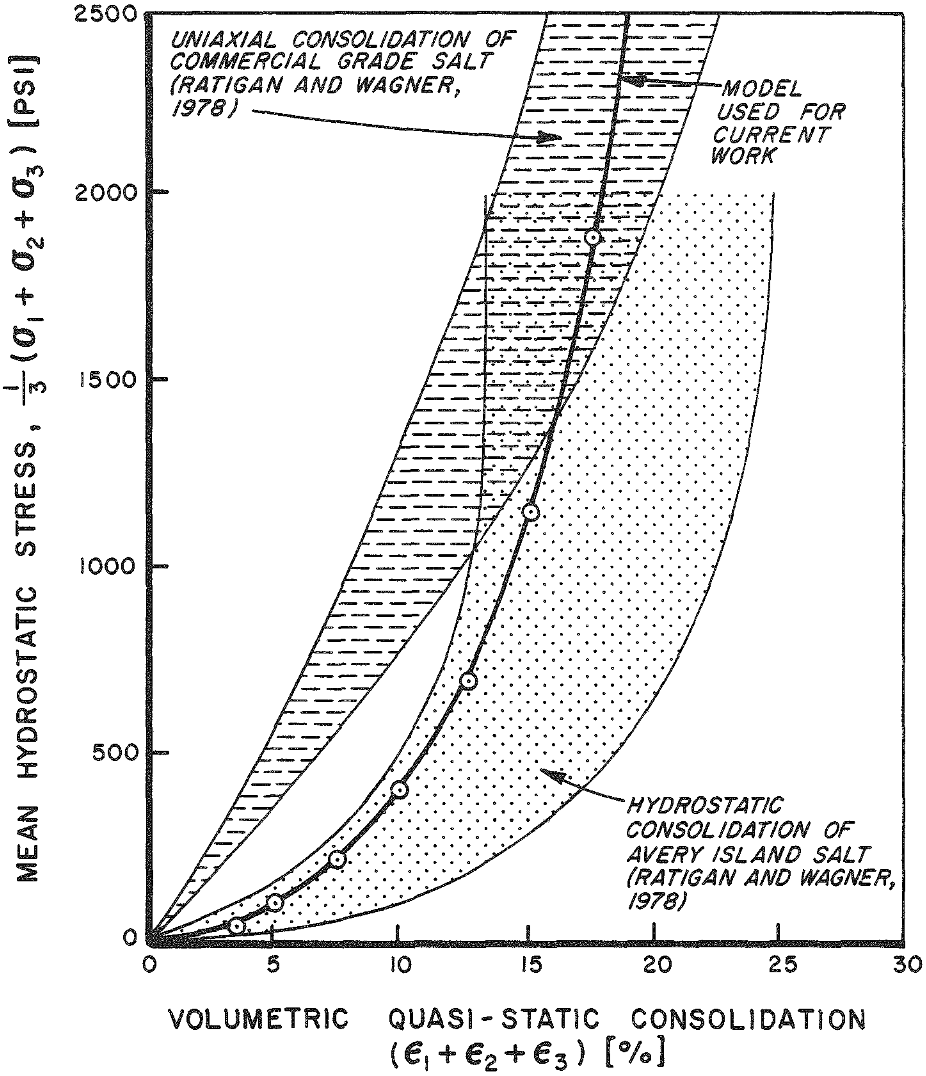

Figure A-1. Volumetric Quasi-Static Consolidation of Granulated Salt as a Function of Mean Normal Stress over a Temperature Range of 70° to 400°F reasonable representation of the available experimental data for quasi-static consolidation. The model shown in Figure A-1 is used in the consolidation analyses (Section A.5) to calculate an instantaneous bulk modulus at a specified volumetric consolidation, which in turn is used to calculate the stress exerted by the backfill. Although the data used are considered adequate for present purposes, it is noted that even quasi-static tests may include some component of creep consolidation. In future laboratory tests it would be useful to determine the instantaneous bulk modulus by extrapolation from the dynamic modulus calculated from sonic velocities.

The data in Figure A-1 indicate that the deformations associated with quasi-static consolidation are insufficient to achieve full consolidation of crushed salt with an initial porosity of 41%. Additional consolidation occurs as a result of creep. According to Ratigan and Wagner (1978), the creep consolidation data for the Avery Island and commercial grade crushed salt may be represented by the relation:

$$\dot{e} = A\, e_v^{-m}\, [\sigma_m/\sigma_o]^n [T/T_o]^p \qquad \text{(A-3)}$$

where
$\dot{e}$ = volumetric strain rate (sec.$^{-1}$)
e_v = total volumetric strain
$\sigma_m = \sigma_1 + \sigma_2 + \sigma_3$
σ_1, σ_2, σ_3 = mean hydrostatic stress
T = temperature (°F)
σ_o = constant to normalize stress
T_o = constant to normalize temperature
A = experimental constant (sec.$^{-1}$)
m,n,p = experimentally determined constants

Table A-2 gives values for the constants in Equation (A-3) determined experimentally for Avery Island salt by Ratigan and Wagner.

Table A-2. Values for Parameters in Creep Consolidation Law for Crushed Salt from Avery Island, Louisiana

Parameter	Value	Units
A	7.29×10^{-13}	$sec.^{-1}$
m	3.53	--
n	3.59	--
p	4.87	--
σ_o	1450	psi
T_o	32	°F

According to Ratigan and Wagner, there was considerable scatter in the experimental data and the correlation coefficient from the regression analysis used to determine the constants in Table A-2 was not particularily good. Also, it should be kept in mind that the creep consolidation law is based on a limited number of relatively short duration tests at relatively high stress levels. The form of the law should probably be exponential in order to represent more accurately the asymptotic increase in volumetric strain toward a limiting value and the asymptotic reduction in strain rate toward zero.

A.2.2 Permeability of Crushed Salt

Laboratory test results which relate intrinsic permeability of salt crystal aggregate to porosity and crystal size are reported by Shor et al (1981). Consolidation tests were performed in brine, brine containing $MgCl_2$, and air in order to evaluate the influence of fluid properties. In all cases the reduction in permeability corresponding to a reduction in porosity was found to be greater than would be predicted for a porous medium such as a sand. Consolidation, as indicated by reduction in permeability, was found to be most rapid in brine. Shor et al suggested that the consolidation of crushed salt involves recrystallization and crystal growth, a process analogous to the sintering of metal or ceramic powders.

The relationship developed by Shor et al utilized crushed salt in which the initial particle size for various mixes ranged from 0.01 to 0.03cm. This relationship is used to construct a lower bound intrinsic permeability vs. porosity curve for an average initial particle size of 0.02cm (Figure A-2). Also shown in Figure A-2 is an intrinsic permeability-porosity relationship calculated using Shor et al's relationship for an average particle size of 0.34cm. This particle size falls outside Shor et al's experimental range but corresponds to the average particle size for crushed salt obtained from a mine crusher station reported by Wagner (1980). Because intrinsic permeability is related to the square of average particle size, the curve based on the larger particle size results in intrinsic permeabilities two orders of magnitude greater than the lower bound predictive curve.

Figure A-2 also shows a regression curve for porosity-permeability data obtained from intact rock salt (in the range 0.2-6.0% porosity). The regression analysis indicates a similar trend to the empirical relationship developed by Shor et al with differences attributable to factors such as different average grain sizes, grain size distributions, stress and temperature histories, and probably sample disturbance. The results indicate that the combined effects of reduction in void space and sintering during consolidation can result in very low permeabilities, approaching or equaling values for intact rock salt. Low permeabilities are achieved, however, only at low porosity values. Additional work is justified to measure permeability changes during consolidation (using coarser salt than used by Shor et al) and to evaluate the processes such as recrystallization which occur during consolidation.

For analyses in this report the following porosity-permeability relationship is used (corresponding to the upper curve in Figure A-2):

$$k = Z^2\, 0.0178 \exp(21 + 6 \ln\phi) \qquad \text{(A-4)}$$

where
k = permeability (darcies)
Z = average particle diameter (0.34cm)
ϕ = porosity

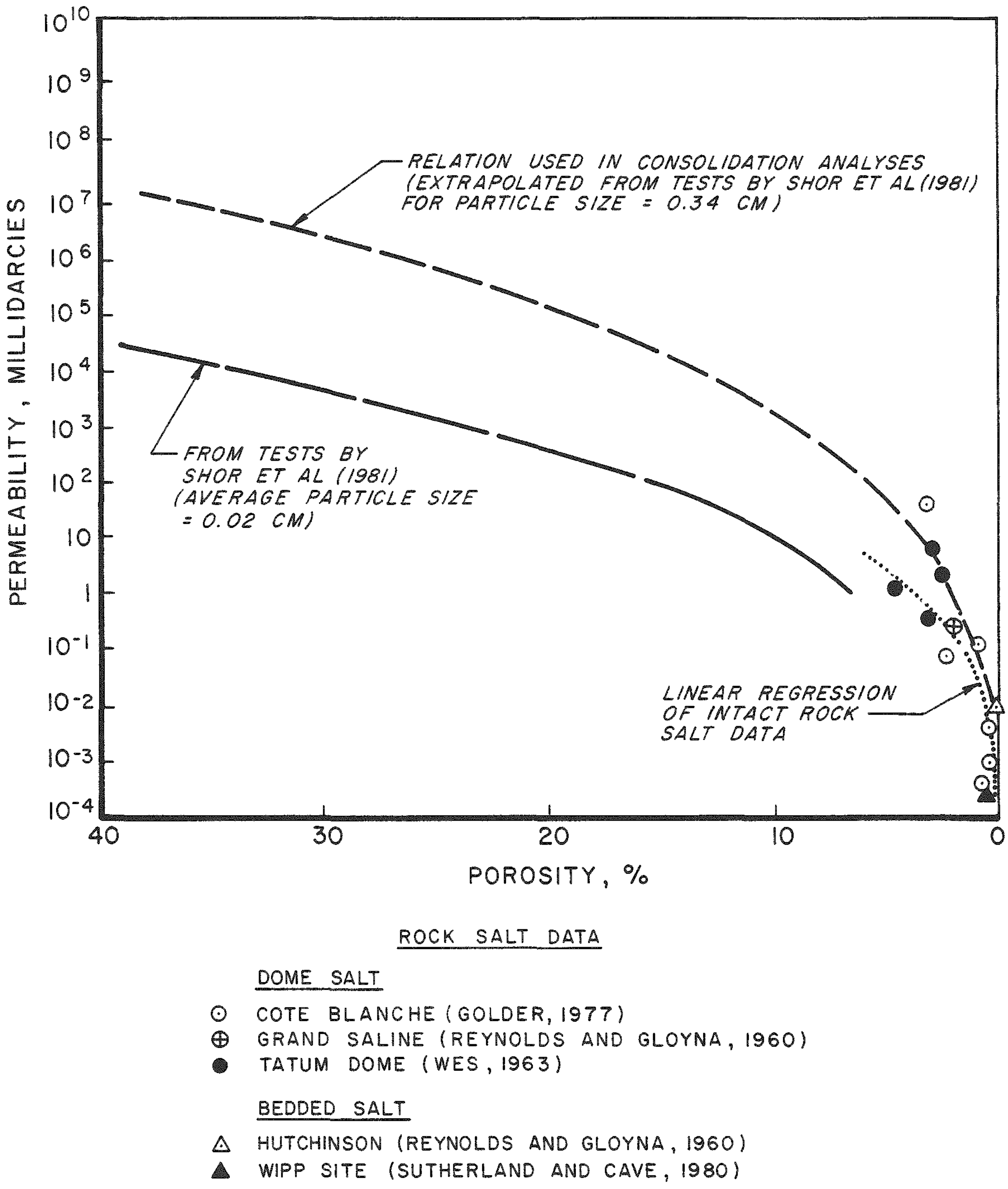

Figure A-2. Permeability of Crushed Salt as a Function of Porosity

A.2.3 Strength of Crushed Salt

Limited test data relating consolidation of crushed salt to unconfined compressive strength are given by Wagner (1980) and Ratigan and Wagner (1978). These data are replotted in Figure A-3 normalized against porosity. Also included are test data obtained from testing of intact rock salt from four dome sites (Avery Island, Cote Blanche, Tatum, Weeks Island) and one bedded salt site (WIPP). In the range of porosity below approximately 20 to 30 percent, the data generally fit well to a curve obtained from Kingery et al (1976) which relates porosity to relative strength (strength at zero porosity = 1) for ceramic materials. This relationship provides further evidence of sintering in the consolidation process in that the crushed salt appears to behave as a porous solid rather than as a densely compacted granular material. It can be seen from Figure A-3 that the intact bedded salt from the WIPP site has a lower strength than the dome salts with the same porosity. There are insufficient data to establish this as a general trend for dome and bedded salts.

A.2.4 Fracture Healing

Tests to evaluate fracture healing in salt have been conducted at Sandia (Costin and Wawersik, 1980). Preliminary results indicated that healing is effective within a few days when samples are heated in the range 22°C to 100°C and subjected to confining stresses up to 35 MPa. The Sandia tests evaluated fracture healing in terms of fracture toughness, a parameter which indicates the resistance to crack propagation along an existing fracture. The results do not indicate permeability directly, although it appears likely that permeability should be reduced significantly along fractures which exhibit high values (approaching values for intact specimens) for fracture toughness. For confining stresses towards the high end of the range tested, Costin and Wawersik found that fractures in salt would heal to the extent that the resistance to crack propagation along the preexisting fracture was about 70 to 80 percent of the resistance to cracking through unfractured material. Healing was found to occur within a matter of days. In the test with the lowest temperature and confining stress (22°C, 10 MPa), the strength along the

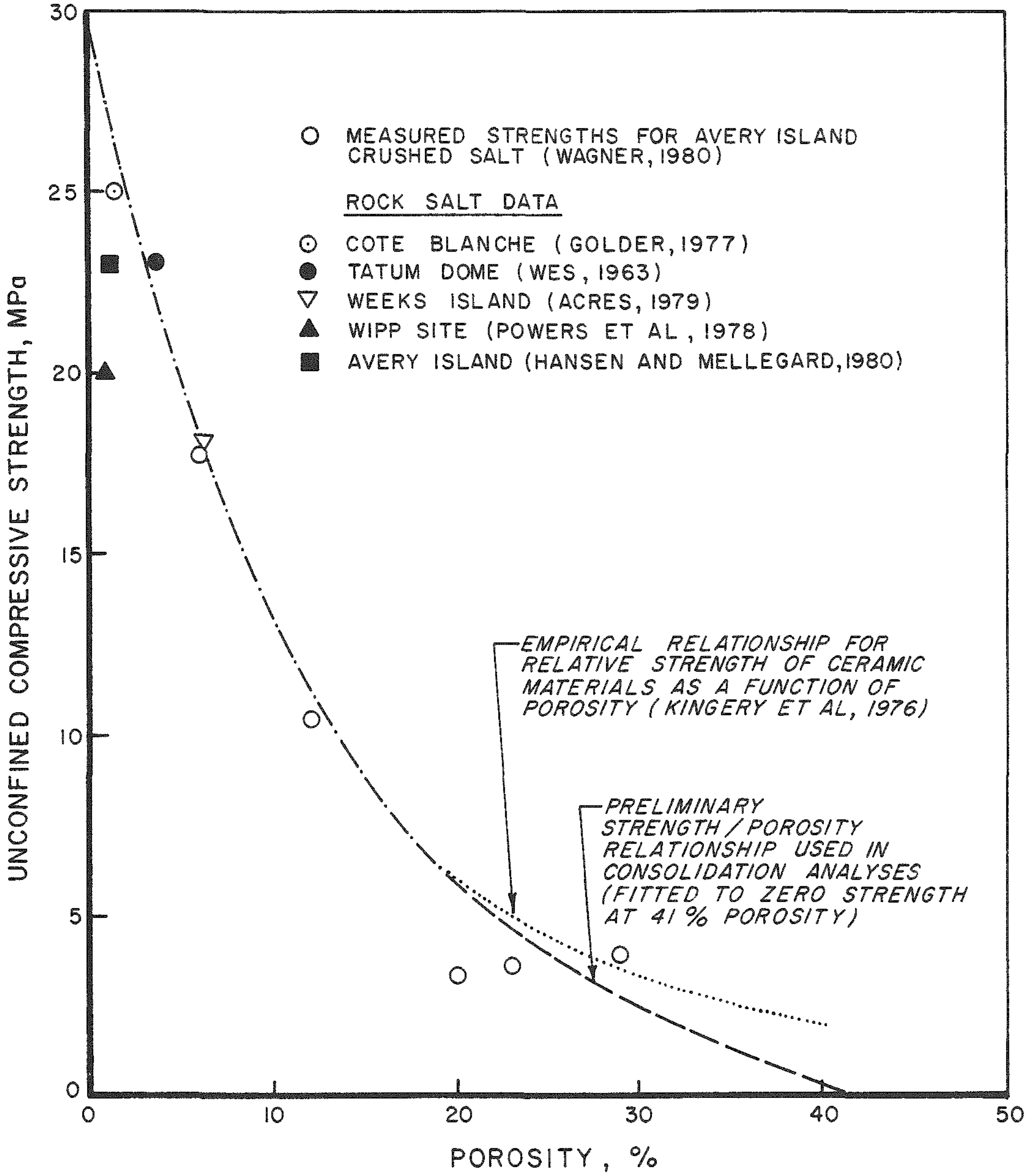

Figure A-3. Unconfined Compressive Strength of Crushed Salt as a Function of Porosity fracture was in the range 20 to 30 percent of the intact strength. This is considered an encouraging result given the short duration of the test.

Costin and Wawersik concluded that healing occurs as a result of creep and interlocking of asperities, although it appears possible that recrystallization might also have some influence. Further tests to measure permeability of healed fractures are planned at Sandia.

A.3 TEMPERATURE HISTORIES AT SEAL LOCATIONS

Heat transfer analyses have been performed to determine temperature histories for various potential seal locations at intervals following waste emplacement (Figure A-4). The analyses calculate the temperature increases due to waste emplacement above the ambient temperature (34°C) at the repository depth. These analyses are simplified as follows:

- Analyses are based on the superposition of closed-form analytical solutions for linear heat conduction from infinite strip power sources in the plane of the repository, and in an infinite medium.

- Thermal properties (obtained from Callahan, 1981) are constant with respect to temperature; values used are as follows:

  - thermal diffusivity $2.96 \times 10^{-6}\ m^2/s$
  - thermal conductivity $5.45\ W/m^2K$

- Thermal properties are isotropic and homogeneous throughout the rock mass (i.e., no allowance is made for interbeds in the salt or for a change in lithology above the salt within the zone of influence of the repository).

- Backfill materials are assigned the same properties as the host rock.

The analyses are conducted for the conceptual repository layout developed by Kaiser (1978) with the shafts located centrally between two main storage areas. Temperature histories are calculated for potential seal locations (Figure A-4), a main access tunnel within the repository,

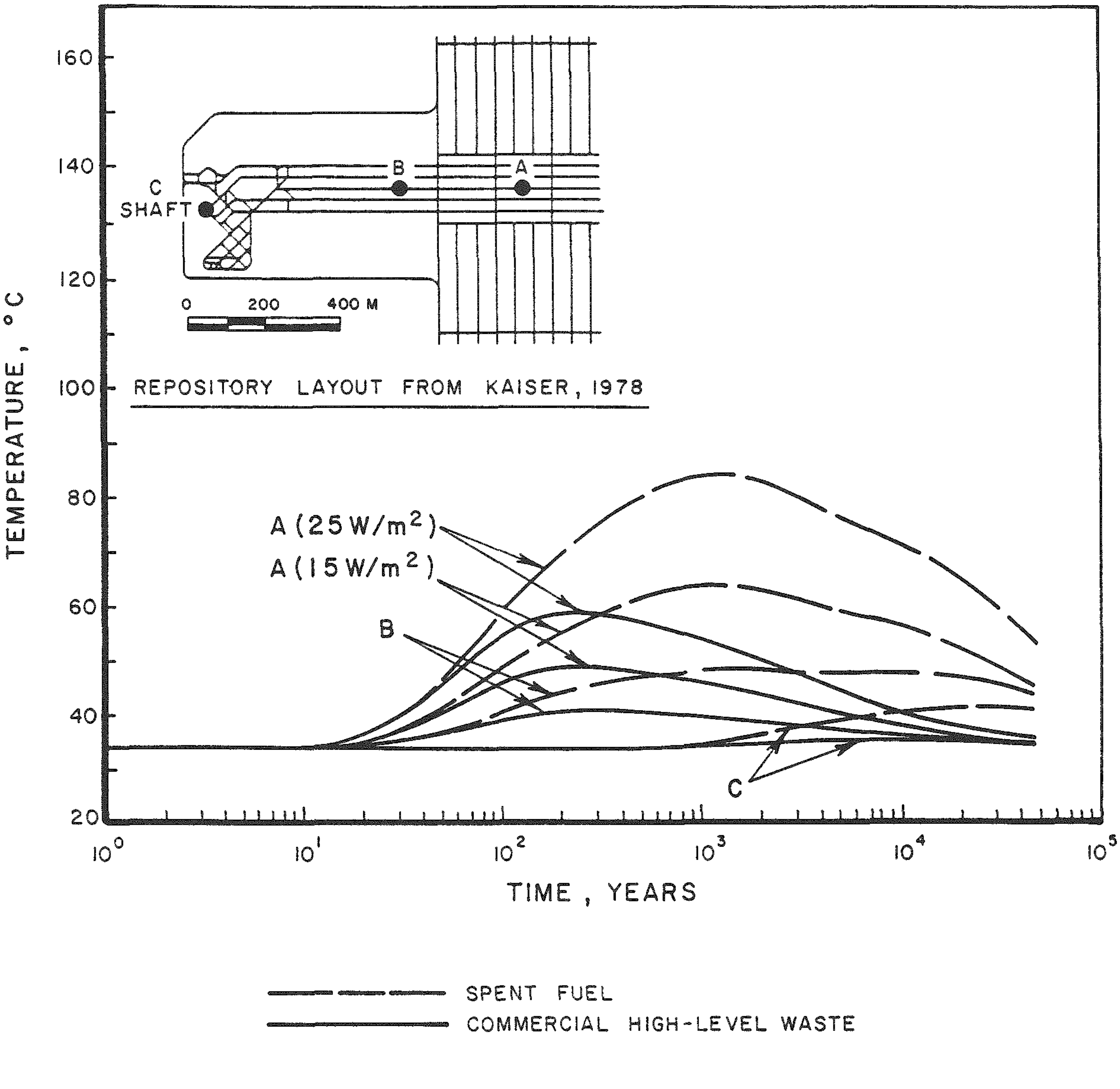

Figure A-4. Approximate Temperature Histories for Potential Seal Locations - Reference Salt Repository a boundary seal location 100m from the edge of the storage area, and the base of a shaft. Temperature histories are calculated for both spent fuel and commercial high-level waste (CHLW) with a heat-loading density of 15 W/m^2 used for all three locations. For the location within the repository, temperatures are also calculated for a heat loading density of 25 W/m^2 to account for locally higher loadings close to the storage rooms.

Power decay curves for spent fuel and CHLW are based on data given by Raines et al (1981) and Slate et al (1981) respectively. In the latter case it was necessary to interpolate a complete power decay curve from the limited data given in the reference. Because the repository is modeled as an infinite strip source, the analysis is considered conservative in predicting higher peak temperatures than those that will occur in practice. (These higher temperatures will tend to increase predicted consolidation rates but the error is considered to be minor.) Figure A-4 shows that the maximum temperature reached at a seal location in the main access tunnels (with a heat loading of 25 W/m^2) is approximately 85°C for spent fuel and 60°C for CHLW. The maximum is attained after 1000 years for spent fuel and after 200 years for CHLW. Maximum temperatures are significantly lower in the shaft pillar. For example, at the base of the shaft the maximum attained is 40°C for spent fuel and 36°C for CHLW. For both types of waste, there is essentially no temperature increase at the base of the shaft for about 1000 years following waste emplacement.

A.4 CLOSURE RATES

The driving mechanism for consolidation of the salt backfill is closure of the shaft or tunnel due to salt creep. Simplified analyses of room closure have been performed using a closed form solution for radial displacement of an infinitely long cylinder in an infinite medium (Chabannes, 1982). The closed form solution accounts for secondary creep which is dependent on both stress and temperature. The general solution for the rate of radial displacement (w) at any radius is:

$$w = -E_c \left(\frac{\sqrt{3}}{2}\right)^{n+1} \left(\frac{2a^{2/n}(P_o - P_i)}{n\sigma_c \, r^{2/n}}\right)^n r \qquad \text{(A-5)}$$

where:

E_c = A exp(-Q/RT),

A = creep constant (Table A-3)

Q = activation energy,

T = absolute temperature,

R = universal gas constant,

n = stress exponent,

σ_c = constant used to normalize stress in creep law,

a = radius of the penetration,

r = radius,

P_o = farfield stress, assumed to be hydrostatic, and

P_i = internal radial stress applied to the surface of the the penetration.

For the condition in which the internal stress is zero, the displacement rate (i.e., closure rate) at the surface of the opening is given by:

$$w = -E_c \left(\frac{\sqrt{3}}{2}\right)^{n+1} \left(\frac{2P_o}{n\sigma_c}\right)^n a \qquad \text{(A-6)}$$

The analysis considered two types of rocksalt: bedded salt from southeastern New Mexico (SENM), and dome salt from Avery Island. Material properties for these salts are shown in Table A-3, along with two other salts for which creep data are available, Tatum Dome and Asse. It can be seen that there is a significant difference between the creep constants of the SENM and Avery Island salts.

The analysis used a farfield stress of 13.8 MPa (corresponding approximately to 2000 feet depth) and a unit reference stress (used to normalize stresses in Equation A-5) of 1MPa. Radial displacement was converted to volumetric closure by integrating the displacement rate

Table A-3. Summary of Values for Parameters in Temperature Dependent Secondary Creep Law

Salt Type	A $1/MPa^n$-day	Q Calories/ mole	n	Reference
Avery Island	0.00564	8099	4.11	Mellegard and Senseny, 1981
Tatum Dome	1.3555	11550	4.29	Chabannes, 1982
ASSE	0.1813	12900	5.00	Herrmann et al, 1980
SENM Type A*	0.1254	12000	4.90	Herrmann et al, 1980
SENM Type B*	0.1005	12000	4.90	Herrmann et al, 1980

* Salt from 2150 feet depth (WIPP Site).

**Salt from 2600 feet depth (WIPP Site).

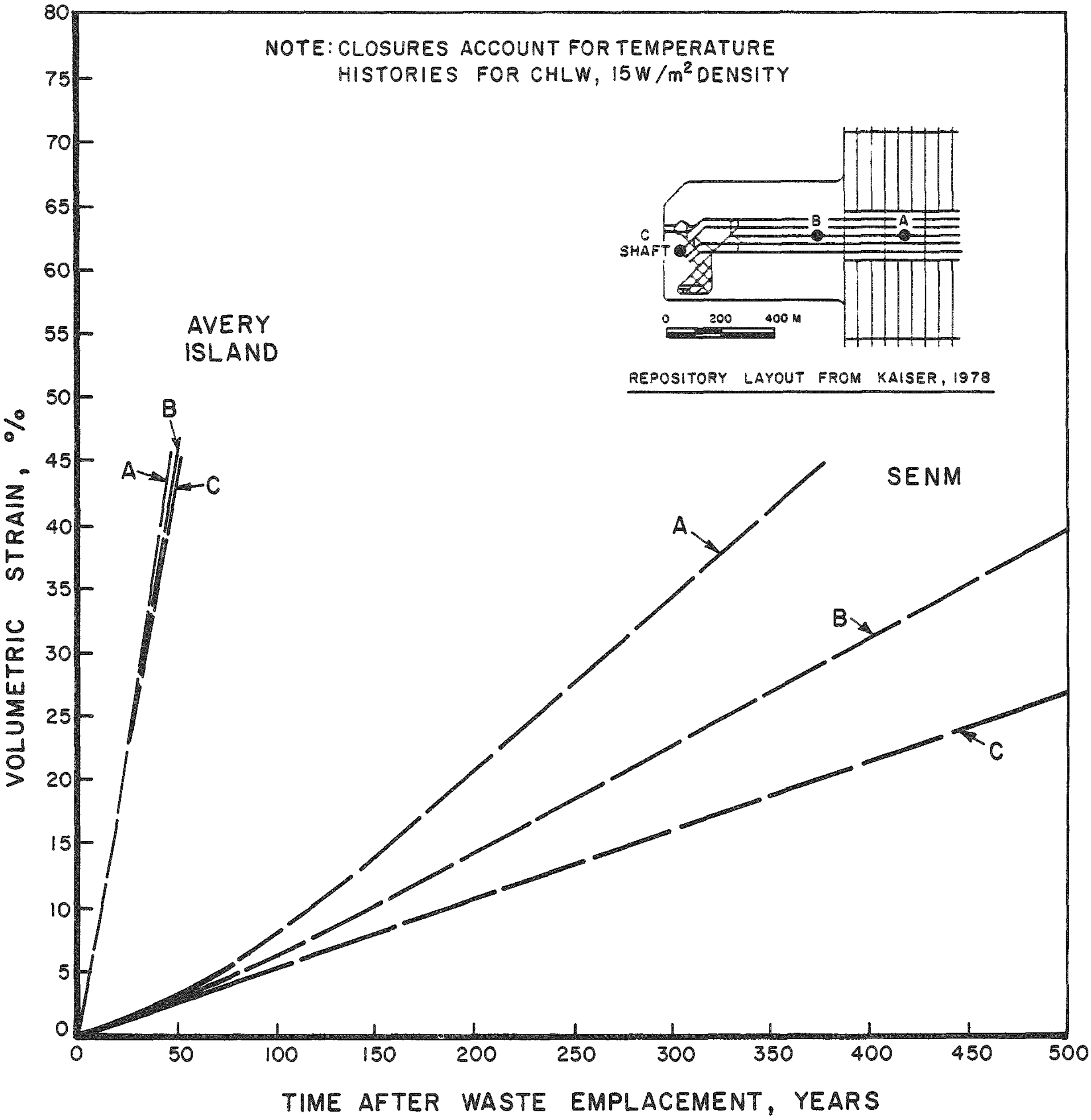

Figure A-5. Cumulative Volumetric Closure at Specified Seal Locations for Southeast New Mexico (SENM) and Avery Island Salt sections than for circular openings due to the presence of reentrant corners. Also, the times required for closure for locations within the repository will be less if the backfill is placed a long time (50 to 100 years) following waste emplacement when temperatures and creep rates will be higher.

A.5 CONSOLIDATION OF CRUSHED SALT BACKFILL

A.5.1 Analytical Method, Assumptions, and Input Parameters

Consolidation versus time analyses for crushed salt backfill have been performed for the potential seal locations described previously. The analysis of consolidation as a function of time was performed by solving Equation (A-5) in an incremental fashion. The internal pressure P_i at the beginning of each incremental step is updated based on the following expression:

$$\Delta P_i = B_T \left[\Delta e_v - \Delta e_{vc}\right] \qquad \text{(A-7)}$$

where ΔP_i is the incremental change in the pressure P_i exerted by the backfill on the surface of the opening, B_T is the tangent bulk modulus (Equation A-2) which is based on the total volumetric strain at the beginning of the time step, Δe_v is the increment of total volumetric strain, and Δe_{vc} is the increment of creep consolidation calculated using Equation (A-3) and the time increment for the current step. The total volumetric strain and the mean stress used in Equation (A-5) are based on values at the beginning of the step. Temperatures used in Equations (A-3) and (A-5) are mid-interval values obtained by linear interpolation using the temperature histories described in Section A.3. As described in Section A.4, the radius r in Equation (A-5) is based on the deformed geometry at the beginning of the time step.

The porosity of the crushed salt backfill is given by the following relationship:

$$\phi = e_c - e_v - e_I \qquad \text{(A-8)}$$

where e_c = the total volumetric strain required to achieve intact properties

Table A-4. Approximate Times Required to Close Air Gaps at the Ceilings of Backfilled Tunnels

Salt*	Gap Size (m)	Spent Fuel			CHLW		
		Panel	Edge	Shaft	Panel	Edge	Shaft
SENM (type A)	0.3	100	130	160	100	130	160
	0.6	160	220	330	170	240	330
	1.0	220	330	540	260	380	540
Avery Island	0.3	10	10	10	10	10	10
	0.6	20	20	20	20	20	20
	1.0	30	30	30	30	30	30

All times in years following backfill emplacement for tunnel 5.5m wide x 3.4m high.

*See Table A-3 for properties.

e_v = the current volumetric strain

e_I = the initial volumetric strain due to compaction at the time of placement

The porosity of intact salt is taken to be 0.6% (corresponding to the porosity of intact bedded salt from Hutchinson, Kansas given by Reynolds and Gloyna, 1960) and the porosity of loosely compacted backfill is 41% (Section A.2.1). For loosely compacted backfill e_c is approximately 40% and e_I is zero. For densely compacted backfill a value of 16% was assumed for e_I corresponding to an initial porosity after compaction of 25%. It is not known at this time if an initial porosity of 25% is achievable in practice.

The changes in permeability and strength related to changes in porosity have been described in Sections A.2.2 and A.2.3 respectively. Analyses have been performed for several types of salt using values for parameters in the secondary creep law given in Table A-3.

There are a number of assumptions and simplifications involved in the approach described above. These include:

- Analyses are for an idealized circular geometry. This is the real case for a shaft, but not for a tunnel in the repository. Volumetric closure rates calculated for a circular opening probably underestimate closures for a rectangular tunnel. On the other hand, consolidation may occur less uniformly throughout a rectangular opening than in a circular opening.

- Backfill and waste are assumed to be emplaced at the same time. In practice the backfill will be placed probably 5 to 50 years following emplacement of the waste in adjacent storage panels. In this case, closure rates and consolidation rates will be faster than those predicted by the current analyses because temperatures will be higher.

- Backfill is emplaced to completely fill the penetration with no air gap at the ceiling.

This is a reasonable assumption for the shaft and access tunnel within the shaft pillar but not for tunnels and storage rooms within the repository where air gaps may be left to maintain ventilation during the period when the waste is required to be retrievable. The time required to close any air gap can be estimated from the results presented in Table A-4 and added to the time required to consolidate the backfill.

- No allowance is made for the effects of pressure build-up of air trapped in voids in the salt.
- The temperature at any given time is assumed to be uniform for both the intact and crushed salt. This is a more reasonable assumption for a seal at the base of the shaft than for a seal in a storage panel.
- The stress field at any time is the stationary or steady state stress field which is only a function of the current internal pressure P_i, the far stress P_o, and the stress exponent n.
- Thermoelastic stresses and their influence on consolidation and closure are ignored.
- As the crushed salt backfill consolidates, it will be able to carry deviatoric stress. This component of stress is ignored when computing the pressure exerted by the backfill against the opening as it consolidates.
- Consolidation characteristics are based on preliminary laboratory data.

A.5.2 Results

There are a number of properties whose variation with time at key seal locations are important when evaluating the performance of crushed salt as a seal material. Changes in porosity (density), permeability, strength, and internal stress are discussed below. As noted above, all analyses assume that the backfill completely fills the penetration initially.

As the penetration closes due to creep, the crushed salt consolidates leading to an increase in density and a decrease in porosity. Figure A-6 shows porosity as a function of time at three potential seal locations for a CHLW repository. As can be seen, the location of the crushed salt backfill (in terms of its proximity to the waste) has a significant impact on the time required to achieve the assumed intact porosity of 0.6%. The change in porosity can be related to concurrent changes in permeability using the porosity-permeability relationship established in Section A.2.2. Figure A-7 shows permeability as a function of time for backfill at the base of the shaft and in a tunnel within the repository for CHLW and for an initial backfill porosity of 41%. It can be noted that low permeabilities are not achieved until the effective porosity is very near the intact porosity. Table A-5 gives a summary of all the results obtained for spent fuel as well as CHLW, and for initial porosities of 25% and 41%. Three preliminary conclusions may be drawn from this table:

- The type of waste (CHLW or spent fuel) has only a minor impact on the times required to achieve intact properties. This arises because the temperature histories for the two types of waste are similar over the period of interest (Figure A-4).

- The initial porosity of the backfill has a significant influence on the time required to achieve intact properties at the base of the shaft but only minor influence within the repository.

- Crushed salt backfill does not provide a reliable short-term seal at the base of the shaft where the time required to achieve intact properties is of the order of 1000 years.

The analyses thus suggest that there is little incentive for compacting the storage room backfill to any significant degree. They also indicate the necessity for providing seal components such as concrete bulkheads or earthfill backfill to provide low permeability in the short term, especially in the shafts.

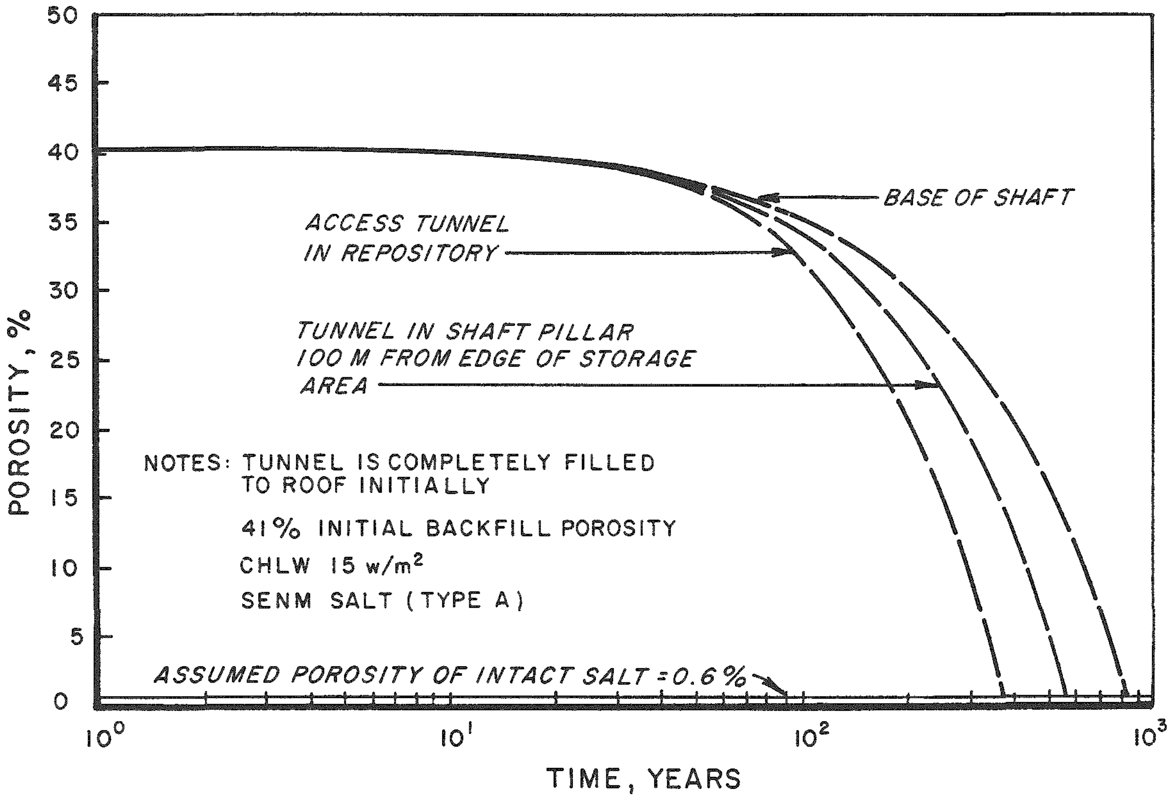

Figure A-6. Reduction in Porosity of Crushed Salt due to Creep Consolidation at Various Seal Locations

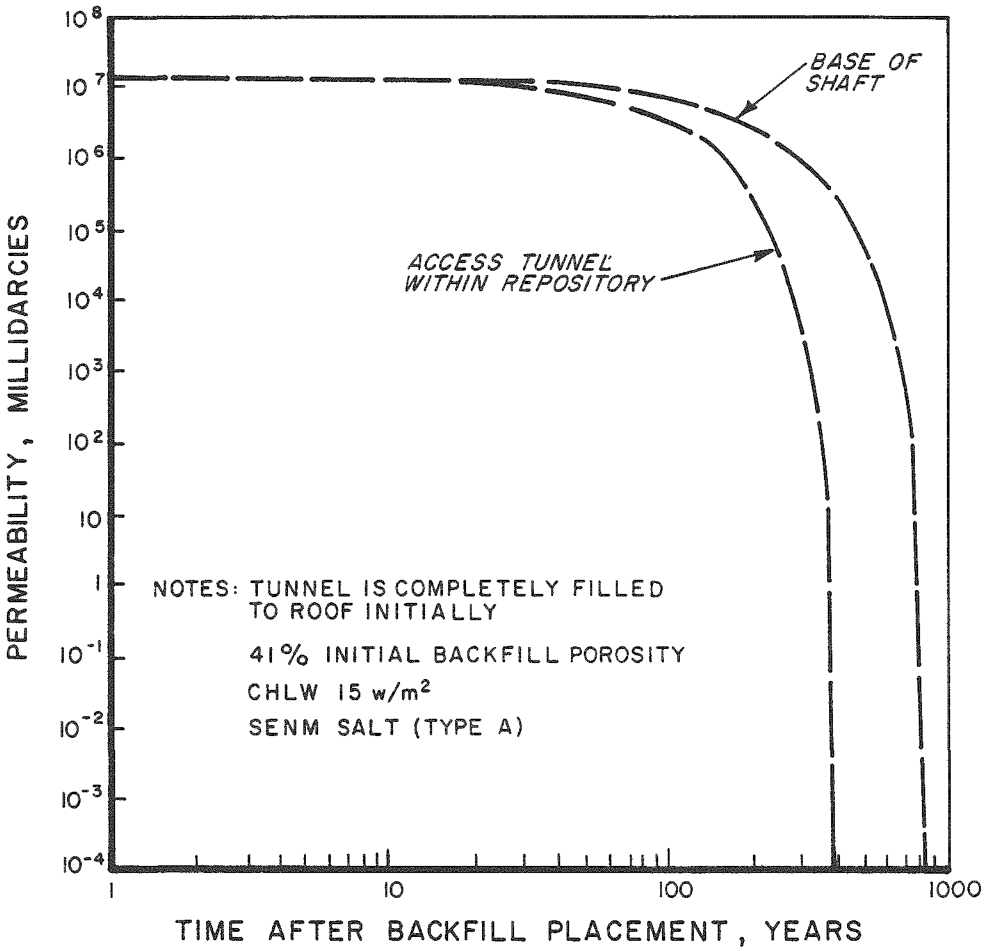

Figure A-7. Reduction in Permeability of Crushed Salt due to Creep Consolidation at 2 Seal Locations

Table A-5. Time Required to Consolidate Crushed Salt to Intact Permeability at Key Sealing Locations

Location	CHLW		Spent Fuel	
	41% Initial ϕ	25% Initial ϕ	41% Initial ϕ	25% Initial ϕ
Base of Shaft	840	530	830	530
100m from Edge of Storage Area	570	370	470	320
Access Tunnel in Repository ($15W/m^2$)	380	250	290	220
Access Tunnel in Repository ($25W/m^2$)	250	180	200	160

Analyses for secondary creep of SENM salt (type A).

Time in years

Preliminary data described in Section A.2.1 indicate that salts which have dissimilar intact creep behavior have similar consolidation characteristics. Nonetheless, a primary factor which will affect the time required to reach intact permeability (other than location and shape of the opening) will be the creep characteristics of the intact salt. Table A-6 compares the time required to reach 0.6% porosity and hence

Table A-6. Time Required to Consolidate Crushed Salt to Intact Permeability at the Base of the Shaft

Salt Type	Time (years)
Avery Island	60
Tatum Dome	60
ASSE	2230
SENM (type A)	840
SENM (type B)	1030

intact permeability at the base of the shaft for several types of salt, in all cases for CHLW. The values for the parameters in the secondary creep law used to compute these times are summarized in Table A-3. As can be seen, the time required to reach intact properties is very sensitive to the properties of the intact salt. This points out that salts with fast creep rates are advantageous from a sealing perspective, although they may not be advantageous with respect to repository operation.

Another important consideration is the magnitude of the stress exerted by the backfill on the surface of the opening as it consolidates. If the stress is high enough, it could help to heal any fractures induced in the host rock around the opening by stress relief or the excavation process (see Section A.2). Figure A-8 shows pressure histories in the crushed salt at potential seal locations for a CHLW repository. As can be seen, the stress level in the crushed salt remains relatively low (less than 1 MPa) prior to reaching intact properties. Once intact properties are reached, however, the pressure builds rapidly with 60% of

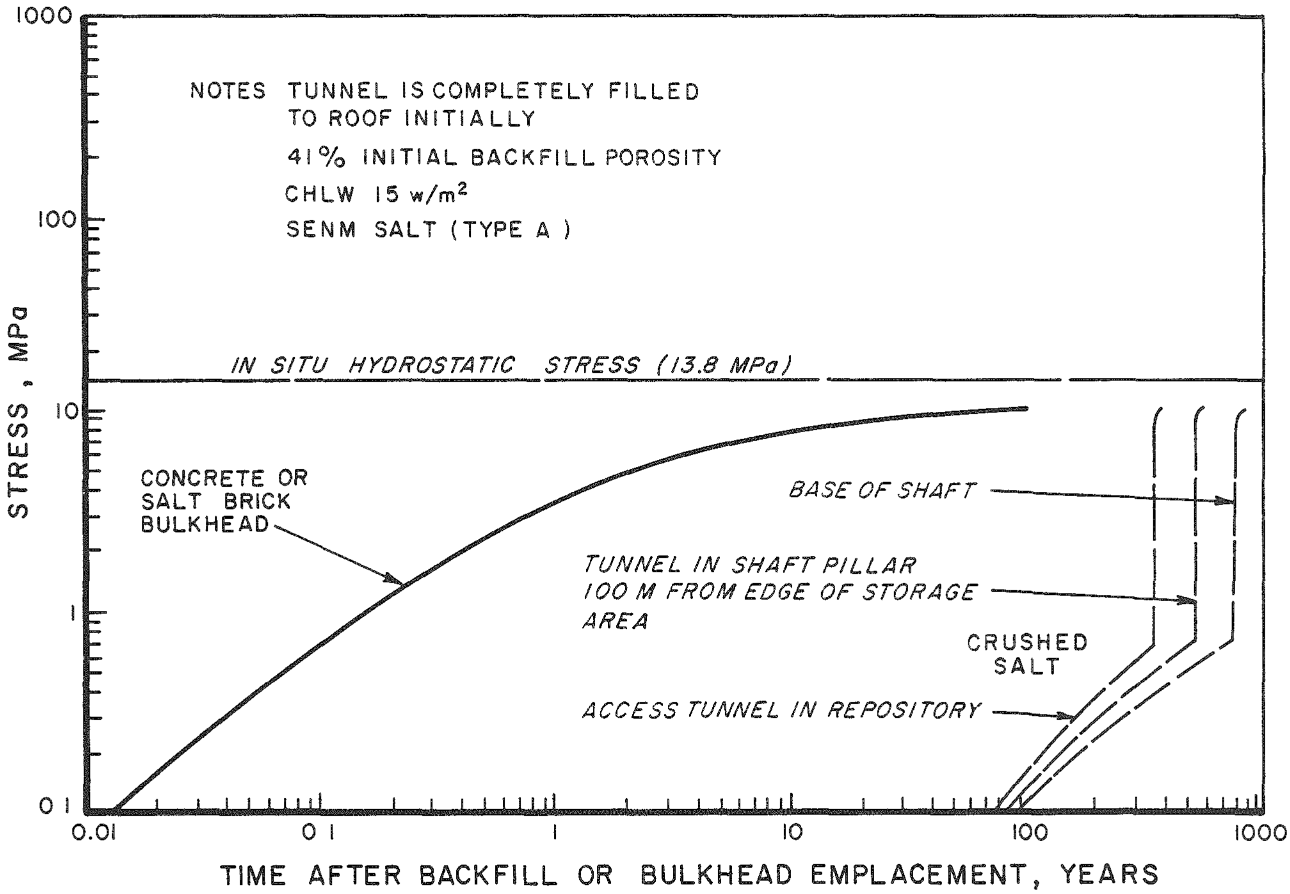

Figure A-8. Radial Stress Buildup on Bulkhead and Pressure Buildup Within Crushed Salt the lithostatic stress reached in a few years. The low stress levels in the crushed salt raises questions about the level of confidence in the creep consolidation law which is based on tests run at much higher mean stress levels.

Given the predicted changes in porosity due to consolidation (Figure A-6), changes in the strength of the backfill can be estimated from the relationship in Figure A-3. For SENM salt, the analyses indicate that the strength of crushed salt placed within the repository will be less than 20% of the strength of intact salt for a period of about 200 years following backfill emplacement (Figure A-9). The strength increases rapidly and approaches the intact strength within the following 100 years. The increase in strength will be more rapid for Avery Island salt.

A.6 STRESS ANALYSIS OF BULKHEADS PLACED IN SALT

A.6.1 Analytical Method, Assumptions, and Input Parameters

An important consideration in the design of a bulkhead to be placed in salt is the radial stress buildup at the interface between the bulkhead and the penetration. As pointed out in the previous section, if this stress is high enough, it will tend to heal any fractures induced in the host rock near the penetration surface by stress relief or the excavation process.

The technique used to evaluate the radial stress buildup at the interface is similar to the approach used to model crushed salt consolidation described in Section A.5.1. In this case, however, the internal pressure P_i is updated by adding the incremental stress ΔP_i computed by the following expression:

$$\Delta P_i = E \, \Delta u / a \qquad \text{(A-9)}$$

where E is the elastic modulus of the bulkhead material, Δu is the incremental change in radial closure, and a is the radius of the penetrated based on the deformed geometry.

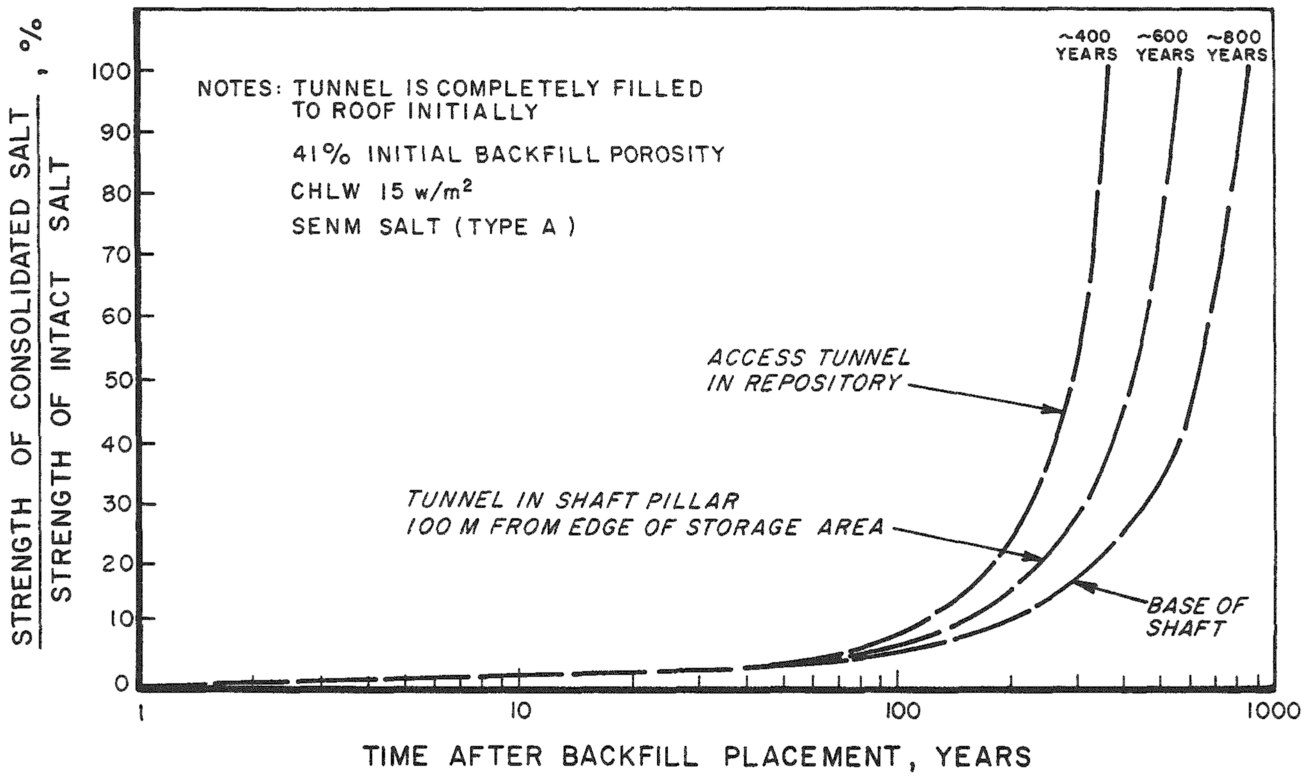

Figure A-9. Increase in Strength of Crushed Salt due to Creep Consolidation at Various Seal Locations

The assumptions implied by this approach are similar to those for the analysis of the consolidation of crushed salt backfill. These include:

- The temperature at any given time is assumed to be uniform for both the bulkhead and the intact salt.
- The stress field at any time is the stationary or steady state stress field which is only a function of the current internal pressure P, the far field stress P_o, and the stress exponent n.
- Thermoelastic stresses are ignored.
- Shear stresses at the interface are not taken into account.

Creep of the host rock is assumed to be the dominant deformational mechanism which overrides any tendency for separation at the bulkhead-rock interface in response to incompatibilities in thermoelastic properties. The importance of differences in thermoelastic properties should be further investigated.

For the purposes of these analyses, the intact salt was assumed to have the properties of SENM (type A) salt. The bulkhead was assumed to behave elastically. For one case it was assumed to be made of concrete with a modulus of 27600 MPa, and for the second case it was assumed to be made of salt bricks with a modulus of 31000 MPa. The assumption that the salt bricks behave elastically is considered reasonable because similar results were obtained from a more elaborate finite element analysis which did account for the creep behavior of the salt bricks.

A.6.2 Results

Of the three sealing locations considered in the previous analyses, the base of the shaft represents the most conservative case to evaluate in that the temperature rise at this location is minimal. Table A-7 gives the time required to reach a given radial stress at the interface for concrete bulkheads. Because the assigned elastic properties of the concrete and salt bricks are essentially the same, the stress histories are virtually identical for the two types of bulkhead.

It is significant that the radial stress reaches 50% of the initial in situ stress in less than 10 years. Based on the limited testing of fracture healing reported in Section A.2.4, it can be reasonably concluded that any fractures in the salt adjacent to the penetration should be at least significantly closed if not totally healed at this stress level. Figure A-8 contrasts the radial stress buildup for the bulkhead against the pressure buildup in the crushed salt backfill. As can be seen, the rate of stress buildup for the bulkhead is very rapid initially but slows down considerably as the initial in situ stress is approached. This is due to the progressive reduction in the effective deviatoric stress which is the primary driving mechanism for creep closure within the host rock. The buildup of radial stress at other seal locations closer to the storage area would be more rapid because of the higher temperatures at these locations.

Table A-7. Radial Stress Buildup on a Concrete Bulkhead At the Base of a Shaft

Time (yrs)	Radial Stress* (MPa)	Fraction of Initial Hydrostatic Stress
0.2	1.38	0.10
0.6	2.76	0.20
1.4	4.14	0.30
3.0	5.52	0.40
6.6	6.90	0.50
16.4	8.27	0.60
51.3	9.65	0.70
104.7	10.34	0.75

*Based on secondary creep law for SENM Salt (type A).

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