APPENDIX I2
APPENDIX A

MATERIAL SPECIFICATION

SHAFT SEALING SYSTEM
COMPLIANCE SUBMITTAL DESIGN REPORT

(This page intentionally blank)

APPENDIX I2
APPENDIX A

MATERIAL SPECIFICATION

SHAFT SEALING SYSTEM
COMPLIANCE SUBMITTAL DESIGN REPORT

Appendix A Abstract

This appendix specifies material characteristics for shaft seal system components designed for the Waste Isolation Pilot Plant. The shaft seal system will not be constructed for decades; however, if it were to be constructed in the near term, materials specified here could be placed in the shaft and meet performance specifications. A material specification is necessary today to establish a frame of reference for design and analysis activities and to provide a basis for seal material parameters. This document was used by three integrated working groups: (1) the architect/engineer for development of construction methods and supporting infrastructure, (2) fluid flow and structural analysis personnel for evaluation of seal system adequacy, and (3) technical staff to develop probability distribution functions for use in performance assessment. The architect/engineers provide design drawings, construction methods and schedules as appendices to the final shaft seal system design report, called the *Compliance Submittal Design Report* (Permit Attachment I2). Similarly, analyses of structural aspects of the design and fluid flow calculations comprise other appendices to the final design report (not included in this Permit Attachment). These products together are produced to demonstrate the adequacy of the shaft seal system to independent reviewers, regulators, and stakeholders. It is recognized that actual placement of shaft seals is many years in the future, so design, planned construction method, and components will almost certainly change between now and the time that detailed construction specifications are prepared for the bidding process. Specifications provided here are likely to guide future work between now and the time of construction, perhaps benefiting from optimization studies, technological advancements, or experimental demonstrations.

(This page intentionally blank)

CONTENTS

Figures

Tables

A1. Introduction

This appendix provides a body of technical information for each of the WIPP shaft seal system materials identified in the text of the *Compliance Submittal Design Report* (Permit Attachment I2). This material specification characterizes each seal material, establishes why it will function adequately, states briefly how each component will be placed, and quantifies expected characteristics, particularly permeability, pertinent to a WIPP-specific shaft seal design. Each material is first described from an engineering viewpoint, then appropriate properties are summarized in tables and figures which emphasize permeability parameter distribution functions used in performance calculations. Materials are discussed beyond limits normally found in conventional construction specifications. Descriptive elements focus on stringent shaft seal system requirements that are vital to regulatory compliance demonstration. Information normally contained in an engineering *performance specification* is included because more than one construction method, or even a completely different material, may function adequately. Content that would eventually be included contractually in *specifications for materials* or *specifications for workmanship* are not included in detail. The goal of these specifications is to substantiate why materials used in this seal system design will limit fluid flow and thereby adequately limit releases of hazardous constituents from the WIPP site at the point of compliance defined in Permit Module V and limit releases of radionuclides at the regulatory boundary.

Figure I2A-1 is a schematic drawing of the proposed WIPP shaft sealing system. Design detail and other characteristics of the geologic, hydrologic and chemical setting are provided in the main body of Permit Attachment I2, other appendices, and references. The four shafts will be entirely filled with dense materials possessing low permeability and other desirable engineering and economic attributes. Seal materials include concrete, clay, asphalt, and compacted salt. Other construction and fill materials include cementitious grout and earthen fill. The level of detail included for each material, and the emphasis of detail, vary among the materials. Concrete, clay, and asphalt are common construction materials used extensively in hydrologic applications. Their descriptions will be rather complete, and performance expectations will be drawn from the literature and site-specific references. Portland cement concrete is the most common structural material being proposed for the WIPP shaft seal system and its use has a long history. Considerable specific detail is provided for concrete because it is salt-saturated. Clay is used extensively in the seal system. Clay is often specified in industry as a construction material, and bentonitic clay has been widely specified as a low permeability liner for hazardous waste sites. Therefore, a considerable body of information is available for clay materials, particularly bentonite. Asphalt is a widely used paving and waterproofing material, so its specification here reflects industry practice. It has been used to seal shaft linings as a filler between the concrete and the surrounding rock, but has not been used as a full shaft seal component. Compaction and natural reconsolidation of crushed salt are uniquely applied here. Therefore, the crushed salt specification provides additional information on its constitutive behavior and sealing performance. Cementitious grout is also specified in some detail because it has been developed and tested for WIPP-specific applications and similar international waste programs. Earthen fill will be given only cursory specifications here because it has little impact on the shaft seal performance and placement to nominal standards is easily attained.

Discussion of each material is divided into sections, which are described in the annotated bullets below:

Functions

A general summary of functions of specific seal components is presented. Each seal component must function within a natural setting, so design considerations embrace naturally occurring characteristics of the surrounding rock.

Material Characteristics

Constitution of the seal material is described and key physical, chemical, mechanical, hydrological, and thermal features are discussed.

Construction

A brief mention is made regarding construction, which is more thoroughly treated in Appendix B of the *Compliance Submittal Design Report* (Permit Attachment I2, Appendix B). Construction, as discussed in this section, is primarily concerned with proper placement of materials. A viable construction procedure that will attain placement specifications is identified, but such a specification does not preclude other potential methods from use when the seal system is eventually constructed.

Performance Requirements

Regulations to which the WIPP must comply do not provide quantitative specifications applicable to seal design. Performance of the WIPP repository is judged against performance standards for miscellaneous units specified in 20.4.1.500 NMAC (incorporating 40 CFR §264.601) for releases of hazardous constituents at the point of compliance defined in Permit Module V. Performance is also judged against potential releases of radionuclides at the regulatory boundary, which is a probabilistic calculation. To this end, probability distribution functions for permeabilities (referred to as PDFs) of each material have been derived for performance assessment of the WIPP system and are included within this subsection on performance requirements.

Verification Methods

It must be assured that seal materials placed in the shaft meet specifications. Both design and selection of materials reflect this principal concern. Assurance is provided by quality control procedures, quality assurance protocol, real-time testing, demonstrations of technology before construction, and personnel training. Materials and construction procedures are kept relatively simple, which creates robustness within the overall system. In addition, elements of the seal system often are extensive in length, and construction will require years to complete. If atypical placement of materials is detected, corrections can be implemented without impacting performance. These specifications limit in situ testing of seal material as it is constructed although, if it is later determined to be desirable, certain in situ tests can be amended in construction specifications. Invasive testing has the potential to compromise the material, add cost, and create logistic and safety problems. Conventional specifications are made for property testing and quality control.

References

These specifications draw on a wealth of information available for each material. Reference to literature values, existing data, anecdotal information, similar applications, laboratory and field testing, and other applicable supportive documentation is made.

A1.1 Sealing Strategy

The shaft seal system design is an integral part of compliance with 20.4.1.500 NMAC (incorporating 40 CFR §264) and 40 CFR §191. The EPA has also promulgated 40 CFR §194, entitled "Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191," to which this design and these specifications are responsive. Other seal design requirements, such as State of New Mexico regulations, apply to stratigraphy above the Salado.

Compliance of the site with 20.4.1.500 NMAC (incorporating 40 CFR §264) and 40 CFR §191 will be determined in part by the ability of the seal system to limit migration of hazardous constituents to the point of compliance defined in Permit Module V, and migration of radionuclides to the regulatory boundary. Both natural and engineered barriers may combine to form the isolation system, with the shaft seal system forming an engineered barrier in a natural setting. Seal system materials possess high durability and compatibility with the host rock. All materials used in the shaft seal system are expected to maintain their integrity for very long periods. The system contains functional redundancy and uses differing materials to reduce uncertainty in performance. Some sealing components are used to retard fluid flow soon after placement, while other components are designed to function well beyond the regulatory period. International programs engaged in research and demonstration of sealant technology provide significant information on longevity of materials similar to those proposed for this shaft seal system (Gray, 1993). When this information is applied to the setting and context of the WIPP, there is strong evidence that the materials specified will maintain their positive attributes for defensibly long periods.

A1.2 Longevity

Longevity of materials is considered within the site geologic and hydrologic setting as summarized in the main body of this report (Permit Attachment I2) and described in the Seal System Design Report (DOE, 1995). A major environmental advantage of the WIPP locality is an overall lack of groundwater to seal against. In terms of sealing the WIPP site, the stratigraphy can be conveniently divided into the Salado Formation and the superincumbent formations comprising primarily the Rustler Formation and the Dewey Lake Redbeds. The Salado Formation, composed mainly of evaporite sequences dominated by halite, is nearly impermeable.

Transmissivity of engineering importance in the Salado Formation is lateral along anhydrite interbeds, basal clays, and fractured zones near underground openings. Neither the Dewey Lake Redbeds nor the Rustler Formation contains regionally productive sources of water, although seepage near the surface in the Exhaust Shaft has been observed. Permeability of materials placed in the Salado below the contact with the Rustler, and their effects on the surrounding disturbed rock zone, are the primary engineering properties of concern. Even though very little regional water is present in the geologic setting, the seal system reflects great concern for groundwater's potential influence on materials comprising the shaft seal system.

Shaft seal materials have been selected in part because of their exceptional durability. However, it is recognized that brine chemistry *could* impact engineered materials if conditions permitted. Highly concentrated saline solutions can, under severe circumstances, affect performance of cementitious materials and clay. Concrete has been shown to degrade under certain conditions, and clays can be more transmissive to brine than to potable water. Asphalt and compacted salt are essentially chemically inert to brine. Although stable in naturally occurring seeps such as those in the Santa Barbara Channel (California), asphalt can degrade when subjected to ultraviolet light or through microbial activity. Brine would not chemically change the compacted salt column, but mechanical effects of pore pressure are of concern to reconsolidation. Mechanical influences of brine on the reconsolidating salt column are discussed in Sections 7 and 8 of the main report (Permit Attachment I2), which summarize Appendices D and C, respectively (Appendices C and D are not included in the Permit, but are contained in Appendix I2 of the permit application).

Because of limited volumes of brine, low hydraulic gradients, and low permeability materials, the geochemical setting will have little influence on shaft seal materials. Each material is durable, though the potential exists for degradation or alteration under extreme conditions. For example, the three major components of portland cement concrete, portlandite ($Ca\ (OH)_2$,) calcium-aluminate-hydrate (CAH) and calcium-silicate-hydrate (CSH), are not thermodynamically compatible with WIPP brines. If large quantities of high ionic strength brine were available and transport of mass was possible, degradation of cementitious phases would certainly occur. Such a localized phenomenon was observed on a construction joint in the liner of the Waste Handling Shaft at the WIPP site. Within the shaft seal system, however, the hydrologic setting does not support such a scenario. Locally brine will undoubtedly contact the surface of mass placements of concrete. A low hydrologic gradient will limit mass transport, although degradation of paste constituents is expected where brine contacts concrete.

Among longevity concerns, degradation of concrete is the most recognized. At this stage of the design, it is established that only small volumes of brine ever reach the concrete elements (see Section 8). Further analysis concerned with borehole plugging using cementitious materials shows that at least 100 pore volumes of brine in an open system would be needed to begin degradation processes. In a closed system, such as the hydrologic setting in the WIPP shafts, phase transformations create a degradation product of increased volume. Net volume increase owing to phase transformation in the absence of mass transport would decrease rather than increase permeability of concrete seal elements.

Mechanical and chemical stability of clays, in this case the emphasis is on bentonitic clay, is particularly favorable in the WIPP geochemical and hydrological environment. A compendium of recent work associated with the Stripa project in Sweden (Gray, 1993) provides field-scale testing results, supportive laboratory experimental data, and thermodynamic modeling that lead to a conclusion that negligible transformation of the bentonite structure will occur over the regulatory period of the WIPP. In fact, very little brine penetration into clay components is expected, based on intermediate-scale experiments at WIPP. Any wetting of bentonite will result in development of swelling pressure, a favorable situation that would accelerate return to a uniform stress state within the clay component.

Natural bentonite is a stable material that generally will not change significantly over a period of ten thousand years. Bentonitic clays have been widely used in field and laboratory experiments concerned with radioactive waste disposal. As noted by Gray (1993), three internal mechanisms, illitization, silicification and charge change, could affect sealing properties of bentonite. Illitization and silicification are thermally driven processes and, following discussion by Gray (1993), are not possible in the environment or time-frame of concern at the WIPP. The naturally occurring Wyoming bentonite which is the specified material for the WIPP shaft seal is well over a million years old. It is, therefore, highly unlikely that metamorphism of bentonite enters as a design concern.

Asphalt has existed for thousands of years as natural seeps. Longevity studies specific to DOE's Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term stability (Wing and Gee, 1994). Asphalt used as a seal component deep in the shaft will inhabit a benign environment, devoid of ultraviolet light or an oxidizing atmosphere. Additional assurance against possible microbial degradation in asphalt elements is mitigated with addition of lime. For these reasons, it is thought that design characteristics of asphalt components will endure well beyond the regulatory period.

Materials being used to form the shaft seals are the same as those being suggested in the scientific and engineering literature as appropriate for sealing deep geologic repositories for radioactive wastes. This fact was noted during independent technical review. Durability or longevity of seal components is a primary concern for any long-term isolation system. Issues of possible degradation have been studied throughout the international community and within waste isolation programs in the USA. Specific degradation studies are not detailed in this document because longevity is one of the over-riding attributes of the materials selected and degradation is not perceived to be likely. However, it is acknowledged here that microbial degradation, seal material interaction, mineral transformation, such as silicification of bentonite, and effects of a thermal pulse from asphalt or hydrating concrete remain areas of continued study.

A2. Material Specifications

The WIPP shaft seal system plays an important role in meeting regulatory requirements such as 20.4.1.500 NMAC (incorporating 40 CFR §§264.111 and 264.601) and 40 CFR 191. A combination of available, durable materials which can be emplaced with low permeability is proposed as the seal system. Components include mass concrete, asphalt waterstops sandwiched between concrete plugs, a column of asphalt, long columns of compacted clay, and a column of compacted crushed WIPP salt. The design is based on common materials and construction technologies that could be implemented using today's technology. In choosing materials, emphasis was given to permeability characteristics and mechanical properties. The function, constitution, construction, performance, and verification of each material are given in the following sections.

A2.1 Mass Concrete

Concrete has exceptionally low permeability and is widely used for hydraulic applications such as water storage tanks, water and sewer systems, and massive dams. Salt-saturated concrete has been used successfully as a seal material in potash and salt mining applications. Upon hydration, unfractured concrete is nearly impermeable, having a permeability less than 10^{-20} m^2. In addition, concrete is a primary structural material used for compression members in countless applications. Use of concrete as a shaft seal component takes advantage of its many attributes and the extensive documentation of its use.

This specification for mass concrete will discuss a special design mixture of a salt-saturated concrete called Salado Mass Concrete or SMC (Wakeley et al., 1995). Performance of SMC and similar salt-saturated mixtures is established and will be completely adequate for concrete applications within the WIPP shafts. Because concrete is such a widely used material, it has been written into specifications many times. Therefore, the specification for SMC contains recognized standard practices, established test methods, quality controls, and other details that are not available at a similar level for other seal materials. Use of salt-saturated concrete, especially SMC, is backed by extensive laboratory and field studies that establish performance characteristics far exceeding requirements of the WIPP shaft seal system.

A2.1.1 Functions

The function of the concrete is to provide a durable component with small void volume, adequate structural compressive strength, and low permeability. Concrete components appear within the shaft seal system at the very bottom, the very top, and several locations in between where they provide a massive plug that fills the opening and a tight interface between the plug and host rock. In addition, concrete is a rigid material that will support overlying seal components while promoting natural healing processes within the salt disturbed rock zone (the DRZ is discussed further in Appendix D of Appendix I2 in the permit application, which is not included in the Permit).

Concrete is one of the redundant components that protects the reconsolidating salt column. Since the salt column will achieve low permeabilities in fewer than 100 years (see Section 2.4.4 of this specification), concrete would no longer be needed after that time. For purposes of performance assessment calculations, a change in concrete permeability to degraded values is "allowed" to occur. However, concrete within the Salado Formation is likely to endure throughout the regulatory period with sustained engineering properties.

All concrete sealing elements, with the exception of a possible concrete cap, are unreinforced. In conventional civil engineering design, reinforcement is used to resist tensile stresses since concrete is weak in tension and reinforcement bar (rebar) balances tensile stresses in the steel with compressive stresses in concrete. However, concrete has exceptional compressive strength, and all the states of stress within the shaft will be dominated by compressive stress. Mass concrete, by definition, is related to any volume of concrete where heat of hydration is a design concern. SMC is tailored to minimize heat of hydration and overall differential temperature. An analysis of hydration heat distribution is included in Appendix D of Appendix I2 in the permit application. Boundary conditions are favorable for reducing any possible thermally induced tensile cracking during the hydration process.

A2.1.2 Material Characteristics

Salt-saturated concrete contains sufficient salt as an aggregate to saturate hydration water with respect to NaCl. Salt-saturated concrete is required for all uses within the Salado Formation because fresh water concrete would dissolve part of the host rock. Dissolution would cause a poor bond and perhaps a more porous interface, at least initially.

Dry materials for SMC include cementitious materials, fine and coarse aggregates, and sodium chloride. Concrete mixture proportions of materials for one cubic yard of concrete appear in Table A-1.

Table A-1. Concrete Mixture Proportions

Material	lb/yd^3
Portland cement	278
Class F fly ash	207
Expansive cement	134
Fine aggregate	1292
Coarse aggregate	1592
Sodium chloride	88
Water	225

$kg/m^3 = (lb/yd^3) * (0.59)$. Water: Cement Ratio is weight of water divided by all cementitious materials.

Table A-2 is a summary of standard specifications for concrete materials. Further discussion of each specification is presented in subsequent text, where additional specifications pertinent to particular concrete components are also given.

Table A-2. Standard Specifications for Concrete Materials

Material	Applicable Standard Tests and Specifications	Comments
Class H oilwell cement	American Petroleum Institute Specification 10	Chemical composition determined according to ASTM C 114
Class F fly ash	ASTM C 618, Standard Specification for Fly Ash	Composition and properties determined according to ASTM C 311
Expansive cement	Similar to ASTM C 845	Composition determined according to ASTM C 114
Salt	ASTM E 534, Chemical Analysis of Sodium Chloride	Batched as dry ingredient, not as an admixture
Coarse and fine aggregates	ASTM C 33, Standard Specification for Concrete Aggregates; ASTM C 294 and C 295 also applied	Moisture content determined by ASTM C 566

Portland cement shall conform to American Petroleum Institute (API) Specification 10 Class G or Class H. Additional requirements for the cement are that the fineness as determined according to ASTM C 204 shall not exceed 300 m^2/kg, and the cement must meet the requirement in ASTM C 150 for moderate heat of hydration.

Fly Ash shall conform to ASTM C 618, Class F, with the additional requirement that the percentage of Ca cannot exceed 10 %.

Expansive cement for shrinkage-compensation shall have properties so that, when used with portland cement, the resulting blend is shrinkage compensating by the mechanism described in ASTM C 845 for Type K cement. Additional requirements for chemical composition of the shrinkage compensating cement appear in Table A-3.

Table A-3. Chemical Composition of Expansive Cement

Chemical composition	Weight %
Magnesium oxide, max	1.0
Calcium oxide, min	38.0
Sulfur trioxide, max	28.0
Aluminum trioxide (AL_2O_3), min	7.0
Silicon dioxide, min	7.0
Insoluble residue, max	1.0
Loss on ignition, max	12.0

Sodium Chloride shall be of a technical grade consisting of a minimum of 99.0 % sodium chloride as determined according to ASTM E 534, and shall have a maximum particle size of 600 µm.

Aggregate proportions are reported here on saturated surface-dry basis. Specific gravity of coarse and fine aggregates used in these proportions were 2.55 and 2.58, respectively. Absorptions used in calculations were 2.25 (coarse) and 0.63 (fine) % by mass. Concrete mixture proportions will be adjusted to accommodate variations in the materials selected, especially differences in specific gravity and absorptions of aggregates. Fine aggregate shall consist of natural silica sand. Coarse aggregate shall consist of gravel. The quantity of flat and elongated particles in the separate size groups of coarse aggregates, as determined by ASTM D 4791, using a value of 3 for width-thickness ratio and length-width ratio, shall not exceed 25 % in any size group. Moisture in the fine and coarse aggregate shall not exceed 0.1 % when determined in accordance with ASTM C 566. Aggregates shall meet the requirements listed in Table A-4.

A2.1.3 Construction

Construction techniques include surface preparation of mass concrete and slickline (a drop pipe from the surface) placement at depth within the shaft. A batching and mixing operation on the surface will produce a wet mixture having initial temperatures not exceeding 20°C. Placement uses a tremie line, where the fresh concrete exits the slickline below the surface level of the concrete being placed. This procedure will minimize entrained air. Placement requires no vibration and, except for the large concrete monolith at the base of each shaft, no form work. No special curing is required for the concrete because its natural environment ensures retention of humidity and excellent hydration conditions. It is desired that each concrete pour be continuous, with the complete volume of each component placed without construction joints. However, no perceivable reduction in performance is anticipated if, for any reason, concrete placement is interrupted. A free face or cold joint could allow lateral flow but would remain perpendicular to flow down the shaft. Further discussion of concrete construction is presented in Appendix B.

Table A-4. Requirements for Salado Mass Concrete Aggregates

Property	Fine Aggregate	Coarse Aggregate
Specific Gravity (ASTM C 127, ASTM C 128)	2.65, max	2.80, max
Absorption (ASTM C 127, ASTM C 128)	1.5 percent, max	3.5 percent, max
Clay Lumps and Friable Particles (ASTM C 142)	3.0 percent, max	3.0 percent, max
Material Finer than 75-μm (No. 200) Sieve (ASTM C 117)	3.0 percent, max	1.0 percent, max
Organic Impurities (ASTM C 40)	No. 3, max	N/A
L.A. Abrasion (ASTM C 131, ASTM C 535)	N/A	50 percent, max
Petrographic Examination (ASTM C 295)	Carbonate mineral aggregates shall not be used	Carbonate rock aggregates shall not be used
Coal and Lignite, less than 2.00 specific gravity (ASTM C 123)	0.5 percent, max	0.5 percent, max

A2.1.4 Performance Requirements

Specifications of concrete properties include characteristics in the green state as well as the hardened state. Properties of hydrated concrete include conventional mechanical properties and projections of permeabilities over hundreds of years, a topic discussed at the end of this section. Table A-5 summarizes target properties for SMC. Attainment of these characteristics has been demonstrated (Wakeley et al., 1995). SMC has a strength of about 40 MPa at 28 days and continues to gain strength after that time, as is typical of hydrating cementitious materials. Concrete strength is naturally much greater than required for shaft seal elements because the state of stress within the shafts is compressional with little shear stress developing. In addition, compressive strength of SMC increases as confining pressure increases (Pfeifle et al., 1996). Volume stability of the SMC is also excellent, which assures a good bond with the salt.

Thermal and constitutive models for the SMC are described in Appendix D of Appendix I2 in the permit application. Thermal properties are fit to laboratory data and used to calculate heat distribution during hydration. An isothermal creep law and an increasing modulus are used to represent the concrete in structural calculations. The resistance established by concrete to inward creep of the Salado Formation accelerates healing of microcracks in the salt. The state of stress impinging on concrete elements within the Salado Formation will approach a lithostatic condition.

Table A-5. Target Properties for Salado Mass Concrete

Property	Comment
Initial slump 10 ± 1.0 in. Slump at 2 hr 8 ± 1.5 in.	ASTM C 143, high slump needed for pumping and placement
Initial temperature ≤ 20°C	ASTM C 1064, using ice as part of mixing water
Air content ≤ 2.0%	ASTM C 231 (Type B meter), tight microstructure and higher strength
Self-leveling	Restrictions on underground placement may preclude vibration
No separately batched admixtures	Simple and reproducible operations
Adiabatic temperature rise ≤ 16°C at 28 days	To reduce thermally induced cracking
30 MPa (4500 psi) compressive strength	ASTM C 39, at 180 days after placement
Volume stability	ASTM C 157, length change between +0.05 and -0.02% through 180 days

Permeability of SMC is very low, consistent with most concretes. Owing to a favorable state of stress and isothermal conditions, the SMC will remain intact. Because little brine is available to alter concrete elements, minimal degradation is possible. Resistance to phase changes of salt-saturated concretes and mortars within the WIPP setting has been excellent. These favorable attributes combine to assure concrete elements within the Salado will remain structurally sound and possess very low permeability for exceedingly long periods.

Permeabilities of SMC and other salt-saturated concretes have been measured in Small-Scale Seal Performance Tests (SSSPT) and Plug Test Matrix (PTM) at the WIPP for a decade and are corroborated by laboratory measurements (e.g., Knowles and Howard, 1996; Pfeifle et al., 1996). From these tests, values and ranges of concrete permeability have been developed. For performance assessments calculations, permeability of SMC seal components is treated as a random variable defined by a log triangular distribution with a best estimator of 1.78×10^{-19} m^2 and lower and upper limits of 2.0×10^{-21} and 1.0×10^{-17} m^2, respectively.

The probability distribution function is shown in Figure I2A-2. Further, it is recognized that concrete function is required for only a relatively short-term period as salt reconsolidates. Concrete is expected to function adequately beyond its design life. For calculational expediency, a higher, very conservative permeability of 1.0×10^{-14} is assigned to concrete after 400 years. This abrupt change in permeability does not imply degradation, but rather reflects system redundancy and the fact that concrete is no longer relied on as a seal component.

A2.1.5 Verification Methods

The concrete supplier shall perform the inspection and tests described below (Tables A-6 and A-7) and, based on the results of these inspections and tests, shall take appropriate action. The laboratory performing verification tests shall be on-site and shall conform with ASTM C 1077. Individuals who sample and test concrete or the constituents of concrete as required in this specification shall have demonstrated a knowledge and ability to perform the necessary test procedures equivalent to the ACI minimum guidelines for certification of Concrete Laboratory Testing Technicians, Grade I. The Buyer will inspect the laboratory, equipment, and test procedures for conformance with ASTM C 1077 prior to start of dry materials batching operations and prior to restarting operations.

A2.1.5.1 Fine Aggregate

(*A) Grading*. Dry materials will be sampled while the batch plant is operating; there shall be a sieve analysis and fineness modulus determination in accordance with ASTM C 136.

(B) Fineness Modulus Control Chart. Results for fineness modulus shall be grouped in sets of three consecutive tests, and the average and range of each group shall be plotted on a control chart. The upper and lower control limits for average shall be drawn 0.10 units above and below the target fineness modulus, and the upper control limit for range shall be 0.20 units above the target fineness modulus.

Table A-6. Test Methods Used for Measuring Concrete Properties During and After Mixing

Property	Test Method	Title
Slump	ASTM C 143	Slump of Portland Cement Concrete
Unit weight	ASTM C 138	Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
Air content	ASTM C 231	Air Content of Freshly Mixed Concrete by the Pressure Method
Mixture temperature	ASTM C 1064	Temperature of Freshly Mixed Concrete

Table A-7. Test Methods Used for Measuring Properties of Hardened Concrete

Property	Test Method	Title
Compressive strength	ASTM C 39	Compressive Strength of Cylindrical Concrete Specimens
Modulus of elasticity	ASTM C 469	Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Volume stability	ASTM C 157	Length Change of Hardened Cement Mortar and Concrete

(C) Corrective Action for Fine Aggregate Grading. When the amount passing any sieve is outside the specification limits, the fine aggregate shall be immediately resampled and retested. If there is another failure for any sieve, the fact shall be immediately reported to the Buyer. Whenever a point on the fineness modulus control chart, either for average or range, is beyond one of the control limits, the frequency of testing shall be doubled. If two consecutive points are beyond the control limits, the process shall be stopped and stock discarded if necessary.

(D) Moisture Content Testing. There shall be at least two tests for moisture content in accordance with ASTM C 566 during each 8-hour period of dry materials batch plant operation.

(E) Moisture Content Corrective Action. Whenever the moisture content of fine aggregate exceeds 0.1 % by weight, the fine aggregate shall be immediately resampled and retested. If there is another failure the batching shall be stopped.

A2.1.5.2 Coarse Aggregate

(A) Grading. Coarse aggregate shall be analyzed in accordance with ASTM C 136.

(B) Corrective Action for Grading. When the amount passing any sieve is outside the specification limits, the coarse aggregate shall be immediately resampled and retested. If the second sample fails on any sieve, that fact shall be reported to the Buyer. Where two consecutive averages of five tests are outside specification limits, the dry materials batch plant operation shall be stopped, and immediate steps shall be taken to correct the grading.

(C) Moisture Content Testing. There shall be at least two tests for moisture content in accordance with ASTM C 566 during each 8-hour period of dry materials batch plant operation.

(D) Moisture Content Corrective Action. Whenever the moisture content of coarse aggregate exceed 0.1 % by weight, the coarse aggregate shall be immediately resampled and retested. If there is another failure, batching shall be stopped.

A2.1.5.3 Batch-Plant Control

The measurement of all constituent materials including cementitious materials, each size of aggregate, and granular sodium chloride shall be continuously controlled. The aggregate batch weights shall be adjusted as necessary to compensate for their nonsaturated surface-dry condition.

A2.1.5.4 Concrete Products

Concrete products will be tested during preparation and after curing as summarized in Tables A-6 and A-7 for preparation and hydrated concrete, respectively.

A2.2 Compacted Clay

Compacted clays are commonly proposed as primary sealing materials for nuclear waste repositories and have been extensively investigated (e.g., Gray, 1993). Compacted clay as a shaft sealing component provides a barrier to brine and possibly to gas flow into or out of the repository and supports the shaft with a high density material to minimize subsidence. In the event that brine does contact the compacted clay columns, bentonitic clay can generate a beneficial swelling pressure. Swelling would increase internal supporting pressure on the shaft wall and accelerate healing of any disturbed rock zone. Wetted, swelling clay will seal fractures as it expands into available space and will ensure tightness between the clay seal component and the shaft walls.

A2.2.1 Functions

In general, clay is used to prevent fluid flow either down or up the shaft. In addition, clay will stabilize the shaft opening and provide a backstress within the Salado Formation that will enhance healing of microfractures in the disturbed rock. Bentonitic clays are specified for Components 4, 8, and 12. In addition to limiting brine migration down the shafts, a primary function of a compacted clay seal through the Rustler Formation (Component 4) is to provide separation of water bearing units. The primary function of the upper Salado clay column (Component 8) is to limit groundwater flow down the shaft, thereby adding assurance that the reconsolidating salt column is protected. The lower Salado compacted clay column (Component 12) will act as a barrier to brine and possibly to gas flow (see construction alternatives in Appendix B) soon after placement and remain a barrier throughout the regulatory period.

A2.2.2 Material Characteristics

The Rustler and Salado compacted clay columns will be constructed of a commercial well-sealing grade sodium bentonite blocks compacted to between 1.8 and 2.0 g/cm^3. An extensive experimental data base exists for the permeability of sodium bentonites under a variety of conditions. Many other properties of sodium bentonite, such as strength, stiffness, and chemical stability also have been thoroughly investigated. Advantages of clays for sealing purposes include low permeability, demonstrated longevity in many types of natural environments, deformability, sorptive capacity, and demonstrated successful utilization in practice for a variety of sealing purposes.

A variety of clays could be considered for WIPP sealing purposes. For WIPP, as for most if not all nuclear waste repository projects, bentonite has been and continues to be a prime candidate as the clay sealing material. Bentonite clay is chosen here because of its overwhelming positive sealing characteristics. Bentonite is a highly plastic swelling clay material (e.g., Mitchell, 1993), consisting predominantly of smectite minerals (e.g., IAEA, 1990). Montmorillonite, the predominant smectite mineral in most bentonites, has the typical plate-like structure characteristic of most clay minerals.

The composition of a typical commercially available sodium bentonite (e.g. Volclay, granular sodium bentonite) contains over 90% montmorillonite and small portions of feldspar, biotite, selenite, etc. A typical sodium bentonite has the chemical composition summarized in Table A-8 (American Colloid Company, 1995). This chemical composition is close to that reported for MX-80 which was used successfully in the Stripa experiments (Gray, 1993). Sodium bentonite has a tri-layer expanding mineral structure of approximately $(Al\ Fe_{1.67}\ Mg_{0.33})\ Si_4O_{10}\ (OH_2)\ Na^+Ca^{++}{}_{0.33}$. Specific gravity of the sodium bentonite is about 2.5. The dry bulk density of granular bentonite is about 1.04 g/cm^3.

Densely compacted bentonite (of the order of 1.75 g/cm^3), when confined, can generate a swelling pressure up to 20 MPa when permeated by water (IAEA, 1990). The magnitude of the swelling pressure generated depends on the chemistry of the permeating water. Laboratory and field measurements suggest that the bentonite specified for shaft seal materials in the Salado may achieve swell pressures of 3 to 4 MPa, and likely substantially less. Swelling pressure in the bentonite column is not expected to be appreciable because little contact with brine fluids is conceivable. Further considerations of potential swelling of bentonite within the Rustler Formation may be appropriate, however.

Table A-8. Representative Bentonite Composition.

Chemical Compound	Weight %
SiO_2	63.0
Al_2O_3	21.1
Fe_2O_3	3.0
FeO	0.4
MgO	2.7
Na_2O	2.6
CaO	0.7
H_2O	5.6
Trace Elements	0.7

Mixtures of bentonite and water can range in rheological characteristics from a virtually Newtonian fluid to a stiff solid, depending on water content. Bentonite can form stiff seals at low moisture content, and can penetrate fractures and cracks when it has a higher water content. Under the latter conditions it can fill void space in the seal itself and disturbed rock zones. Bentonite with dry density of 1.75 g/cm^3 has a cohesion of 5-50 kPa, and a friction angle of 5 to 15° (IAEA, 1990). At density greater than 1.6-1.7 g/cm^3, swelling pressure of bentonite is less affected by the salinity of groundwater providing better chemical and physical stabilities.

A2.2.3 Construction

Seal performance within the Salado Formation is far more important to regulatory compliance than is performance of earthen fill in the overlying formations. Three potential construction methods might be used to place clay in the shaft, as discussed in Appendix B. Construction of bentonite clay components specifies block assembly procedures demonstrated successfully at the WIPP site (Knowles and Howard, 1996) and in a considerable body of work by Roland Pusch (see summary in Gray, 1993). To achieve low permeabilities, dry density of the bentonite blocks should be about 2.0 g/cm^3, although a range of densities is discussed in Section 2.2.4. A high density of clay components is also desirable to carry the weight of overlying seal material effectively and to minimize subsidence.

Placement of clay in the shaft is one area of construction that might be made more cost and time effective through optimization studies. An option to construct clay columns using dynamic compaction will likely prove to be efficient, so it is specified for earthen fill in the Dewey Lake Redbeds (as discussed later) and may prove to be an acceptable placement method for other components. Dynamic compaction would use equipment developed for placement of crushed salt. The Canadian nuclear waste program has conducted extensive testing, both in situ and in large scale laboratory compaction of clay-based barrier materials with dynamic hydraulically powered impact hammers (e.g., Kjartanson et al, 1992). The Swedish program similarly has investigated field compaction of bentonite-based tunnel backfill by means of plate vibrators (e.g., Nilsson, 1985). Both studies demonstrated the feasibility of in situ compaction of bentonite-based materials to a high density. Near surface, conventional compaction methods will be used because insufficient space remains for dynamic compaction using the multi-deck work stage.

A2.2.4 Performance Requirements

The proven characteristics of bentonite assure attainment of very low permeability seals. It is recognized that the local environment contributes to the behavior of compacted clay components. Long-term material stability is a highly desired sealing attribute. Clay components located in brine environments will have to resist cation exchange and material structure alteration. Clay is geochemically mature, reducing likelihood of alteration and imbibition of brine is limited to isolated areas. Compacted clay is designed to withstand possible pressure gradients and to resist erosion and channeling that could conceivably lead to groundwater flow through the seal. Compacted clay seal components support the shaft walls and promote healing of the salt DRZ. Volume expansion or swelling would accelerate healing in the salt. A barrier to gas flow could be constructed if moisture content of approximately 85% of saturation could be achieved.

Permeability of bentonite is inversely correlated to dry density. Figure I2A-3 plots bentonite permeability as a function of reported sample density for sodium bentonite samples. The permeability ranges from approximately 1×10^{-21} to 1×10^{-17} m^2. In all cases, the data in Figure I2A-3 are representative of low ionic strength permeant waters. Data provided in this figure are limited to sodium bentonite and bentonite/sand mixtures with clay content greater than or equal to 50 %. Cheung et al. (1987) report that in bentonite/sand mixtures, sand acts as an inert fraction which does not alter the permeability of the mixture from that of a 100 % bentonite sample at the same equivalent dry density. Also included in Figure I2A-3 are the three point estimates of permeability at dry densities of 1.4, 1.8, and 2.1 g/cm^3 provided by Jaak Daemen of the University of Nevada, Reno, who is actively engaged in WIPP-specific bentonite testing.

A series of in situ tests (SSSPTs) that evaluated compacted bentonite as a sealing material at the WIPP site corroborate data shown in Figure I2A-3. Test Series D tested two 100 % bentonite seals in vertical boreholes within the Salado Formation at the repository horizon. The diameter of each seal was 0.91 m, and the length of each seal was 0.91 m. Cores of the two bentonite seals had initial dry densities of 1.8 and 2.0 g/cm^3. Pressure differentials of 0.72 and 0.32 MPa were maintained across the bentonite seals with a brine reservoir on the upstream (bottom) of the seals for several years.

Over the course of the seal test, no visible brine was observed at the downstream end of the seals. Upon decommissioning the SSSPT, brine penetration was found to be only 15 cm. Determination of the absolute permeability of the bentonite seal was not precise; however, a bounding calculation of 1×10^{-19} m^2 was made by Knowles and Howard (1996).

Beginning with a specified dry density of 1.8 to 2.0 g/cm^3 and Figure I2A-3, a distribution function for clay permeability was developed and is provided in Figure I2A-4. Parameter distribution reflects some conservative assumptions pertaining to WIPP seal applications. The following provide rationale behind the distribution presented in Figure I2A-4.

1. A practical minimum for the distribution can be specified at 1×10^{-21} m^2.
2. If effective dry density of the bentonite emplaced in the seals only varies from 1.8 to 2.0 g/cm^3, then a maximum expected permeability can be extrapolated from Figure I2A-3 as 1×10^{-19} m^2.
3. Uncertainty exists in being able to place massive columns of bentonite to design specifications. To address this uncertainty in a conservative manner, it is assumed that the compacted clay be placed at a dry density as low as 1.6 g/cm^3. At 1.6 g/cm^3, the maximum permeability for the clay would be approximately 5×10^{-19} m^2. Therefore, neglecting salinity effects, a range of permeability from 1×10^{-21} to 5×10^{-19} m^2 with a best estimate of less than 1×10^{-19} m^2 could be reasonably defined (assuming a best estimate emplacement density of 1.8 g/cm^3). It could be argued, based on Figure I2A-3, that a best estimate could be as low as 2×10^{-20}m^2.

Salinity increases bentonite permeability; however, these effects are greatly reduced at the densities specified for the shaft seal. At seawater salinity, Pusch et al. (1989) report the effects on permeability could be as much as a factor of 5 (one-half order of magnitude). To account for salinity effects in a conservative manner, the maximum permeability is increased from 5×10^{-19} to 5×10^{-18} m^2. The best estimate permeability is increased by one-half order of magnitude to 5×10^{-19} m^2. The lower limit is held at 1×10^{-21} m^2. Because salinity effects are greatest at lower densities, the maximum is adjusted one full order of magnitude while the best estimate (assumed to reside at a density of 1.8 g/cm^3) is adjusted one-half of an order.

The four arguments presented above give rise to the permeability cumulative frequency distribution plotted in Figure I2A-4, which summarizes the performance specification for bentonite columns.

A2.2.5 Verification Methods

Verification of specified properties such as density, moisture content or strength of compacted clay seals can be determined by direct access during construction. However, indirect methods are preferred because certain measurements, such as permeability, are likely to be time consuming and invasive. Methods used to verify the quality of emplaced seals will include quality of block production and field measurements of density. As a minimum, standard quality control procedures recommended for compaction operations will be implemented including visual observation, in situ density measurements, and moisture content measurements. Visual observation accompanied by detailed record keeping will assure design procedures are being followed. In situ testing will confirm design objectives are accomplished in the field.

Density measurements of compacted clay shall follow standard procedures such as ASTM D 1556, D 2167, and D 2922. The moisture content of clay blocks shall be calculated based on the water added during mixing and can be confirmed by following ASTM Standard procedures D 2216 and D 3017. It is probable that verification procedures will require modifications to be applicable within the shaft. As a minimum, laboratory testing to certify the above referenced quality control measures will be performed to assure that the field measurements provide reliable results.

A2.3 Asphalt Components

Asphalt is used to prevent water migration down the shaft in two ways: an asphalt column bridging the Rustler/Salado contact and a "waterstop" sandwiched between concrete plugs at three locations within the Salado Formation, two above the salt column and one below the salt column. An asphalt mastic mix (AMM) that contains aggregate is specified for the column while the specification for the waterstop layer is pure asphalt.

Asphalt is a widely used construction material with many desirable properties. Asphalt is a strong cement, is readily adhesive, highly waterproof, and durable. Furthermore, it is a plastic substance that provides controlled flexibility to mixtures of mineral aggregates with which it is usually combined. It is highly resistant to most acids, salts, and alkalis. A number of asphalts and asphalt mixes are available that cover a wide range of viscoelastic properties which allows the properties of the mixture to be designed for a wide range of requirements for each application. These properties are well suited to the requirements of the WIPP shaft seal system.

A2.3.1 Functions

The generic purpose of asphalt seal components above the salt column is to eliminate water migration downward. The asphalt waterstops above the salt column are designed to intersect the DRZ and limit fluid flow. Asphalt is not the lone component preventing flow of brine downward; it functions in tandem with concrete and a compacted clay column. Waterstop Component # 11 located below the salt column would naturally limit upward flow of brine or gas. Concrete abutting the asphalt waterstops provides a rigid element that creates a backstress upon the inward creeping salt, promoting healing within the DRZ. Asphalt is included in the WIPP shaft seal system to reduce uncertainty of system performance by providing redundancy of function while using an alternative material type. The combination of shaft seal components restricts fluid flow up or down to allow time for the salt column to reconsolidate and form a natural fluid-tight seal.

The physical and thermal attributes of asphalt combine to reduce fluid flow processes. The placement fluidity permits asphalt to flow into uneven interstices or fractures along the shaft wall. Asphalt will self-level into a nearly voidless mass. As it cools, the asphalt will eventually cease flowing. The elevated temperature and thermal mass of the asphalt will enhance creep deformation of the salt and promote healing of the DRZ surrounding the shaft. Asphalt adheres tightly to most materials, eliminating flow along the interface between the seal material and the surrounding rock.

A2.3.2 Material Characteristics

The asphalt column specified for the WIPP seal system is an AMM commonly used for hydraulic structures. The AMM is a mixture of asphalt, sand, and hydrated lime. The asphalt content of AMM is higher than those used in typical hot mix asphalt concrete (pavements). High asphalt contents (10-20% by weight) and fine, well-graded aggregate (sand and mineral fillers) are used to obtain a near voidless mix. A low void content ensures a material with extremely low water permeability because there are a minimum number of connected pathways for brine migration.

A number of different asphaltic construction materials, including hot mix asphalt concrete (HMAC), neat asphalt, and AMMs, were evaluated for use in the WIPP seal design. HMAC was eliminated because of construction difficulty that might have led to questionable performance. An AMM is selected as a preferred alternative for the asphalt columns because it has economic and performance advantages over the other asphaltic options. Aggregate and mineral fines in the AMM increase rigidity and strength of the asphalt seal component, thereby enhancing the potential to heal the DRZ and reducing shrinkage relative to neat asphalt.

Viscosity of the AMM is an important physical property affecting construction and performance. The AMM is designed to have low enough viscosity to be pumpable at application temperatures and able to flow readily into voids. High viscosity of the AMM at operating temperatures prevents long-term flow, although none is expected. Hydrated lime is included in the mix design to increase the stability of the material, decrease moisture susceptibility, and act as an anti-microbial agent. Table A-9 details the mix design specifications for the AMM.

The asphalt used in the waterstop is AR-4000, a graded asphalt of intermediate viscosity. The waterstop uses pure, or neat, asphalt because it is a relatively small volume when compared to the column.

A2.3.3 Construction

Construction of asphalt seal components can be accomplished using a slickline process where the molten material is effectively pumped into the shaft. The AMM will be mixed at ground level in a pug mill at approximately 180°C. At this temperature the material is readily pourable. The AMM will be slicklined and placed using a heated and insulated tremie line. The AMM will easily flow into irregularities in the surface of the shaft or open fractures until the AMM cools. After cooling, flow into surface irregularities in the shaft and DRZ will slow considerably because of the sand and mineral filler components in the AMM and the temperature dependence of the viscosity of the asphalt. AMM requires no compaction in construction. Neat asphalt will be placed in a similar fashion.

The technology to pump AMM is available as described in the construction procedures in Appendix B. One potential problem with this method of construction is ensuring that the slickline remains heated throughout the construction phase. Impedance heating (a current construction technique) can be used to ensure the pipe remains at temperatures sufficient to promote flow. The lower section (say 10 m) of the pipe may not need to be heated, and it may not be desirable to heat it as it is routinely immersed in the molten asphalt during construction to minimize air entrainment. Construction using large volumes of hot asphalt would be facilitated by placement in sections. After several meters of asphalt are placed, the slickline would be retracted by two lengths of pipe and pumping resumed. Once installed, the asphalt components will cool; the column will require several months to approach ambient conditions. Calculations of cooling times and plots of isotherms for the asphalt column are given in Appendix D of Appendix I2 in the permit application. It should be noted that a thermal pulse into the surrounding rock salt could produce positive rock mechanics conditions. Fractures will heal much faster owing to thermally activated dislocation motion and diffusion. Salt itself will creep inward at a much greater rate as well.

Table A-9. Asphalt Component Specifications

AMM Composition:	20 wt% asphalt (AR-4000 graded asphalt) 70 wt% aggregate (silicate sand) 10 wt% hydrated lime	
Aggregate (% passing by weight)		
US Sieve Size		Specification Limits
2.36 mm	(No. 8)	100
1.18 mm	(No. 16)	90
600	(No. 30)	55-75
300	(No. 50)	35-50
150	(No. 100)	15-30
75	(No. 200)	5-15
Mineral Filler: Hydrated Lime Chemical Composition:		
Total active lime content (% by weight)		min. 90.0%
Unhydrated lime weight (% by weight CaO)		max. 5.0%
Free water (% by weight H_2O)		max. 4.0%
Residue Analysis:		
Residue retained on No. 6 sieve		max. 0.1%
Residue retained on No. 30 sieve		max. 3.0%

A2.3.4 Performance Requirements

Asphalt components are required to endure for about 100 years as an interim seal while the compacted salt component reconsolidates to create a very low permeability seal component. Since asphalt will not be subjected to ultraviolet light or an oxidizing environment, it is expected to provide an effective brine seal for several centuries. Air voids should be less than 2% to ensure low permeability. Asphalt mixtures do not become measurably permeable to water until voids approach 8% (Brown, 1990).

At Hanford, experiments are ongoing on the development of a passive surface barrier designed to isolate wastes (in this case to prevent downward flux of water and upward flux of gases) for 1000 years with no maintenance. The surface barrier uses asphalt as one of many horizontal components because low-air-void, high-asphalt-content materials are noted for low permeability and improved mechanically stable compositions. The design objective of this asphalt concrete was to limit infiltration to 1.6×10^{-9} cm/s (1.6×10^{-11} m/s, or for fresh water, an intrinsic permeability of 1.6×10^{-18} m^2). The asphalt component of the barrier is composed of a 15 cm layer of asphaltic concrete overlain with a 5-mm layer of fluid-applied asphalt. The reported hydraulic conductivity of the asphalt concrete is estimated to be 1×10^{-9} m/s (equivalent to an intrinsic permeability of approximately 1×10^{-16} m^2 assuming fresh water). Myers and Duranceau (1994) report that the hydraulic conductivity of fluid-applied asphalt is estimated to be 1.0×10^{-11} to 1.0×10^{-10} cm/s (equivalent to an intrinsic permeability of approximately 1.0×10^{-20} to 1.0×10^{-19} m^2 assuming fresh water).

Consideration of published values results in a lowest practical permeability of 1×10^{-21} m^2. The upper limit of the asphalt seal permeability is assumed to be 1×10^{-18} m^2. Intrinsic permeability of the asphalt column is defined as a log triangular distributed parameter, with a best estimate value of 1×10^{-20} m^2 , a minimum value of 1×10^{-21} m^2, and a maximum value of 1×10^{-18} m^2, as shown in Figure I2A-5. It is recognized that the halite DRZ in the uppermost portion of the Salado Formation is not likely to heal because creep of salt is relatively slow.

These values are used in performance assessment of regulatory compliance analyses and in fluid flow calculations (Appendix C of Appendix I2 in the permit application) pertaining to seal system functional evaluation (Appendix C is not included in the Permit). Other calculations pertaining to rock mechanics and structural considerations of asphalt elements are discussed in Appendix D of Appendix I2 in the permit application.

A2.3.5 Verification Methods

Viscosity of the AMM must be low enough for easy delivery through a heated slickline. Sufficient text book information is available to assure performance of the asphalt component; however, laboratory validation tests may be desirable before installation. There are no plans to test asphalt components after they are placed. With that in mind, some general tests identified below would add quantitative documentation to expected performance values and have direct application to WIPP. The types and objectives of the verification tests are:

Mix Design. A standard mix design which evaluates a combination of asphalt and aggregate mixtures would quantify density, air voids, viscosity, and permeability. Although the specified mixture will function adequately, studies could optimize the mix design.

Viscoelastic Properties at Service Temperatures. Viscoelastic properties over the range of expected service temperatures would refine the rheological model.

Accelerated Aging Analysis. Asphalt longevity issues could be further addressed by using the approach detailed in PNL-Report 9336 (Freeman and Romine, 1994).

Brine Susceptibility Analysis. The presumed inert nature of the asphalt mix can be demonstrated through exposure to groundwater brine solutions found in the Salado Formation. Potential for degradation will be characterized by monitoring the presence of asphalt degradation products in

WIPP brine or brine simulant as a function of time. Effects on hydraulic conductivity can be measured during these experiments.

A2.4 Compacted Salt Column

A reconstituted salt column has been proposed as a primary means to isolate for several decades those repositories containing hazardous materials situated in evaporite sequences. Reuse of salt excavated in the process of creating the underground openings has been advocated since the initial proposal by the NAS in the 1950s. Replacing the natural material to its original setting ensures physical, chemical, and mechanical compatibility with the host formation. Recent developments in support of the WIPP shaft seal system have produced confirming experimental results, constitutive material laws, and construction methods that substantiate use of a salt column for a low permeability, perfectly compatible seal component.

Numerical models of the shaft and seal system have been used to provide information on the mechanical processes that affect potential pathways and overall performance of the seal system. Several of these types of analyses are developed in Appendix D of Appendix I2 in the permit application. Simulations of the excavated shaft and the compacted salt seal element behavior after placement show that as time passes, the host salt creeps inward, the compacted salt is loaded by the host formation and consolidates, and a back pressure is developed along the shaft wall. The back pressure imparted to the host formation by the compacted salt promotes healing of any microcracks in the host rock. As compacted salt consolidates, density and stiffness increase and permeability decreases.

A2.4.1 Functions

The function of the compacted and reconsolidated salt column is to limit transmission of fluids into or out of the repository for the statutory period of 10,000 years. The functional period starts within a hundred years and lasts essentially forever. After a period of consolidation, the salt column will almost completely retard gas or brine migration within the former shaft opening. A completely consolidated salt column will achieve flow properties indistinguishable from natural Salado salt.

A2.4.2 Material Characteristics

The salt component comprises crushed Salado salt with addition of small amounts of water. No admixtures other than water are needed to meet design specifications. Natural Salado salt (also called WIPP salt) is typical of most salts in the Permian Basin: it has an overall composition approaching 90-95 % halite with minor clays, carbonate, anhydrite, and other halite minerals. Secondary minerals and other impurities are of little consequence to construction or performance of the compacted salt column as long as the halite content is approximately 90 %.

The total water content of the crushed salt should be approximately 1.5 wt% as it is tamped into place. Field and laboratory testing verified that natural salt can be compacted to significant density ($\rho \geq 0.9$) with addition of these modest amounts of water. In situ WIPP salt contains approximately 0.5 wt% water. After it is mined, transported, and stored, some of the connate water is lost to evaporation and dehydration. Water content of the bulk material that would be used for compaction in the shaft is normally quite small, on the order of 0.25 wt%, as measured during compaction demonstrations (Hansen and Ahrens, 1996). Measurements of water content of the salt will be necessary periodically during construction to calibrate the proper amount of water to be added to the salt as it is placed.

Water added to the salt will be sprayed in a fine mist onto the crushed salt as it is cast in each lift. Methods similar to those used in the large-scale compaction demonstration will be developed such that the spray visibly wets the salt grain surfaces. General uniformity of spray is desired. The water has no special chemical requirements for purity. It can be of high quality (drinkable) but need not be potable. Brackish water would suffice because water of any quality would become brackish upon application to the salt.

The mined salt will be crushed and screened to a nominal maximum diameter of 5 mm. Gradation of particles smaller than 5 mm is not of concern because the crushing process will create relatively few fines compared to the act of dynamic compaction. Based on preliminary large-scale demonstrations, excellent compaction was achieved without optimization of particle sizes. It is evident from results of the large compaction demonstration coupled with laboratory studies that initial density can be increased and permeability decreased beyond existing favorable results. Further demonstrations of techniques, including crushing and addition of water may be undertaken in ensuing years between compliance certification and beginning of seal placement.

A2.4.3 Construction

Dynamic compaction is the specified procedure to tamp crushed salt in the shaft. Other techniques of compaction have potential, but their application has not been demonstrated. Deep dynamic compaction provides the greatest energy input to the crushed salt, is easy to apply, and has an effective depth of compactive influence far greater than lift thickness. Dynamic compaction is relatively straightforward and requires a minimal work force. If the number of drops remains constant, diameter and weight of the tamper increases in proportion to the diameter of the shaft. The weight of the tamper is a factor in design of the infrastructure supporting the hoisting apparatus. Larger, heavier tampers require equally stout staging. The construction method outlined in Appendix B balances these opposing criteria. Compaction itself will follow the successful procedure developed in the large-scale compaction demonstration (Hansen and Ahrens, 1996).

Transport of crushed salt to the working level can be accomplished by dropping it down a slickline. As noted, additional water will be sprayed onto the crushed salt at the bottom of the shaft as it is placed. Lift heights of approximately 2 m are specified, though greater depths could be compacted effectively using dynamic compaction. Uneven piles of salt can be hand leveled.

A2.4.4 Performance Requirements

Compacted crushed salt is a unique seal material because it consolidates naturally as the host formation creeps inward. As the crushed salt consolidates, void space diminishes, density increases, and permeability decreases. Thus, sealing effectiveness of the compacted salt column will improve with time. Laboratory testing over the last decade has shown that pulverized salt specimens can be compressed to high densities and low permeabilities (Brodsky et al., 1996). In addition, consolidated crushed salt uniquely guarantees chemical and mechanical compatibility with the host salt formation. Therefore, crushed salt will provide a seal that will function essentially forever once the consolidation process is completed. Primary performance results of these analyses include plots of fractional density as a function of depth and time for the crushed salt column and permeability distribution functions that will be used for performance assessment calculations. These performance results are summarized near the end of this section, following a limited background discussion.

To predict performance, a constitutive model for crushed salt is required. To this end, a technical evaluation of potential crushed salt constitutive models was completed (Callahan et al., 1996). Ten potential crushed salt constitutive models were identified in a literature search to describe the phenomenological and micromechanical processes governing consolidation of crushed salt. Three of the ten potential models were selected for rigorous comparisons to a specially developed, although somewhat limited, database. The database contained data from hydrostatic and shear consolidation laboratory experiments. The experiments provide deformation (strain) data as a function of time under constant stress conditions. Based on volumetric strain measurements from experiments, change in crushed salt density and porosity are known. In some experiments, permeability was also measured, which provides a relationship between density and permeability of crushed salt. Models were fit to the experimental database to determine material parameter values and the model that best represents experimental data.

Modeling has been used to predict consolidating salt density as a function of time and position in the shaft. Position or depth of the calculation is important because creep rates of intact salt and crushed salt are strong functions of stress difference. Analyses made use of a “pineapple” slice structural model at the top (430 m), middle (515 m), and bottom (600 m) of the compacted salt column. Initial fractional density of the compacted crushed salt was 0.90 (1944 kg m^{-3}). The structural model, constitutive material models, boundary conditions, etc. are described in Appendix D of Appendix I2 in the permit application. Modeling results coupled with laboratory-determined relationships between density and permeability were used to develop distribution functions for permeability of the compacted crushed salt column for centuries after seal emplacement.

Analyses used reference engineering values for parameters in the constitutive models (e.g., the creep model for intact salt and consolidation models for crushed salt). Some uncertainty associated with model parameters exists in these constitutive models. Consolidating salt density was quantified by predicting density at specific times using parameter variations. Many of these types of calculations comparing three models for consolidation of crushed salt were performed to quantify performance of the salt column, and the reader is referred to Appendix D of Appendix I2 in the permit application for more detail.

Predictions of fractional density as a function of time and depth are shown in Figure I2A-6. Performance calculations of the seal system require quantification of the resultant salt permeability. The permeability can be derived from the experimental data presented in Figure I2A-7. This plot depicts probabilistic lines through the experimental data. From these lines, distribution functions can be derived. Permeability of the compacted salt column is treated as a transient random variable defined by a log triangular distribution. Distribution functions were provided for 0, 50, 100, 200, and 400 years after seal emplacement, assuming that fluids in the salt column pores spaces would not produce a backstress. The resultant cumulative frequency distribution for seal permeability at the seal mid-height is shown in Figure I2A-8. This method predicts permeabilities ranging from 1×10^{-23} m^2 to 1×10^{-16} m^2. Because crushed salt consolidation will be affected by both mechanical and hydrological processes, detailed calculations were performed. These calculations are presented in Appendices C and D.

Numerical models of the shaft provide density of the compacted salt column as a function of depth and time. From the density-permeability relationship, permeability of the compacted salt seal component can be calculated. Similarly, the extent of the disturbed rock zone around the shaft is provided by numerical models. From field measurements of the halite DRZ, permeability of the DRZ is known as a function of depth and time. These spatial and temporal permeability values provide information required to assess the potential for brine and gas movement in and around the consolidating salt column.

A2.4.5 Verification Methods

Results of the large-scale dynamic compaction demonstration suggest that deep dynamic compaction will produce a dense starting material, and laboratory work and modeling show that compacted salt will reconsolidate within several decades to an essentially impermeable mass. As with other seal components, testing of the material in situ will be difficult and probably not the best way to ensure quality of the seal element. This is particularly apparent for the compacted salt component because the compactive effort produces a finely powdered layer on the top of each lift. It turns out that the fine powder compacts into a very dense material when the next lift is compacted. The best way to ensure that the crushed salt element functions properly is to establish performance through QA/QC procedures. If crushed salt is placed with a reasonable uniformity of water and is compacted with sufficient energy, long-term performance can be assured.

Periodic measurements of the water content of loose salt as it is placed in lifts will be used for verification and quality control. Thickness of lifts will be controlled. Energy imparted to each lift will be documented by logging drop patterns and drop height. If deemed necessary, visual inspection of the tamped salt can be made by human access. The powder layer can be shoveled aside and hardness of underlying material can be qualitatively determined or tested. Overall geometric measurements made from the original surface of each lift could be used to approximate compacted density.

A2.5 Cementitious Grout

Cementitious grouting is specified for all concrete members in response to external review suggestions. Grouting is also used in advance of liner removal to stabilize the ground. Cementitious grout is specified because of its proven performance, nontoxicity, and previous use at the WIPP.

A2.5.1 Functions

The function of grout is to stabilize the surrounding rock before existing concrete liners are removed. Grout will fill fractures within adjacent lithologies, thereby adding strength and reducing permeability. Grout around concrete members of the concrete asphalt waterstop will be employed in an attempt to tighten the interface and fill microcracks in the DRZ. Efficacy of grouting will be determined during construction. In addition, reduction of local permeability will further limit groundwater influx into the shaft during construction. Concrete plugs are planned for specific elevations in the lined portion of each shaft. The formation behind the concrete liner will be grouted from approximately 3 m below to 3 m above the plug positions to ensure stability of any loose rock.

A2.5.2 Material Characteristics

The grout developed for use in the shaft seal system has the following characteristics:

- no water separation upon hydration,
- low permeability paste,
- fine particle size,
- low hydrational heat,
- no measurable agglomeration subsequent to mixing,
- two hours of injectability subsequent to mixing,
- short set time,
- high compressive strength, and
- competitive cost.

A cementitious grout developed by Ahrens and coworkers (Ahrens et al., 1996) is specified for application in the shaft seal design. This grout consists of portland cement, pumice as a pozollanic material, and superplasticizer in the proportions listed in Table A-10. The ultrafine grout is mixed in a colloidal grout mixer, with a water to components ratio (W:C) of 0.6:1. Grout has been produced with 90 % of the particles smaller than 5 microns and an average particle size of 2 microns. The extremely small particle size enables the grout to penetrate fractures with apertures as small as 6 microns.

Table A-10. Ultrafine Grout Mix Specification

Component	Weight Percent (wt%)
Type 5 portland cement	45
Pumice	55
Superplasticizer	1.5

A2.5.3 Construction

Grout holes will be drilled in a spin pattern that extends from 3 m below to 3 m above that portion of the lining to be removed. The drilling and grouting sequence will be defined in the workmanship specifications prior to construction. Grout will be mixed on surface and transferred to the work deck via the slick line. Maximum injection pressure will be lithostatic, less 50 psig. It is estimated that four holes can be drilled and grouted per shift.

A2.5.4 Performance Requirements

Performance of grout is not a consideration for compliance issues. Grouting is used to facilitate construction by stabilizing any loose rock behind the concrete liner. If the country rock is fractured, grouting will reduce the permeability of the DRZ significantly. Application at the WIPP demonstrated permeability reduction in an anhydrite marker bed of two to three orders of magnitude (Ahrens et al., 1996). Reduction of local permeability adds to longevity of the grout itself and reduces the possibility of brine contacting seal elements. Because grout does not influence compliance issues, a model for it is not used and has not been developed. General performance achievements are:

- filled fractures as small as 6 microns,
- no water separation upon hydration,
- no evidence of halite dissolution,
- no measurable agglomeration subsequent to mixing,
- one hour of injectability,
- initial Vicat needle set in 2.5 hours,
- compressive strength 40 MPa at 28 days, and
- competitive cost.

A2.5.5 Verification Methods

No verification of the effectiveness of grouting is currently specified. If injection around concrete plugs is possible, an evaluation of quantities and significance of grouting will be made during construction. Procedural specifications will include measurements of fineness and determination of rheology in keeping with processes established during the WIPP demonstration grouting (Ahrens et al., 1996).

A2.6 Earthen Fill

Compacted earthen fill comprise approximately 150 m of shaft fill in the Dewey Lake Redbeds and near surface stratigraphy.

A2.6.1 Functions

There are minimal performance requirements imposed for Components 1 and 3 and none that affect regulatory compliance of the site. Specifications for Components 1 and 3 are general: fill the shaft with relatively dense material to reduce subsidence.

A2.6.2 Material Characteristics

Fill can utilize material that was excavated during shaft sinking and stored at the WIPP site, or a borrow pit may be excavated to secure fill material. The bulk fill material may include bentonite additive, if deemed appropriate.

A2.6.3 Construction

Dynamic compaction is specified for the clay column in the Dewey Lake Formation because of its perceived expediency. Vibratory compaction will be used near surface when there is no longer space for the three stage construction deck.

A2.6.4 Performance Requirements

Care will be taken to compact the earthen fill with an energy of twice Modified Proctor energy, which has been shown to produce a dense, uniform fill.

A2.6.6 Verification

Materials placed will be documented, with density measurements as appropriate.

A3. Concluding Remarks

Material specifications in this appendix provide descriptions of seal materials along with reasoning about why they are expected to function well in the WIPP setting. The specification follows a framework that states the function of the seal component, a description of the material, and a summary of construction techniques that could be implemented without resorting to extensive development efforts. Discussion of performance requirements for each material is the most detailed section because design of the seal system requires analysis of performance to ascertain compliance with regulations. Successful design of the shaft seal system is demonstrated by an evaluation of how well the design performs, rather than by comparison with a predetermined quantity.

Materials chosen for use in the shaft seal system have several common desirable attributes: low permeability, availability, high density, longevity, low cost, constructability, and supporting documentation. Functional redundancy using different materials provides an economically and technologically feasible shaft seal system that limits fluid transport.

A4. References

Ahrens, E.H., T.F. Dale, and R.S. Van Pelt. 1996. *Data Report on the Waste Isolation Pilot Plant Small-Scale Seal Performance Test, Series F Grouting Experiment*. SAND93-1000. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM [SWCF] as WPO37355.)

American Colloid Company. 1995. "Technical Data Sheet. Volclay GPG 30." Arlington Heights, IL: Industrial Chemical Division, American Colloid Company. 1 p. (Copy on file in the SWCF as WPO39636.)

American Petroleum Institute. 1990. "Specification for Materials and Testing for Well Cements." API Specification 10. 5th ed. Washington, DC: American Petroleum Institute. (Available from American Petroleum Institute, 1220 L St. NW, Washington, DC 20005, 202/682-8375.)

ASTM C 33 - 93. "Specification for Concrete Aggregates," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 39 - 94. "Test Method for Compressive Strength of Cylindrical Concrete Specimens," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 40 - 92. "Test Method for Organic Impurities in Fine Aggregates for Concrete," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 114 - 94. "Test Methods for Chemical Analysis of Hydraulic Cement," *Annual Book of ASTM Standards, Volume 04.01, Cement; Lime; Gypsum*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 117 - 95. "Test Method for Material Finer Than 75-:m (No. 200) Sieve in Mineral Aggregates by Washing," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 123 - 94. "Test Method for Lightweight Pieces in Aggregate," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 127 - 88 (1993). "Test Method for Specific Gravity and Absorption of Coarse Aggregate," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 128 - 93. "Test Method for Specific Gravity and Absorption of Fine Aggregate," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 131 - 89. "Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 136 - 95a. "Test Method for Sieve Analysis of Fine and Coarse Aggregates," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 138 - 92. "Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 142 - 78 (1990). "Test Method for Clay Lumps and Friable Particles in Aggregates," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 143 - 90a. "Test Method for Slump of Hydraulic Cement Concrete," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 150 - 95. "Specification for Portland Cement," *Annual Book of ASTM Standards, Volume 04.01, Cement; Lime; Gypsum*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 157 - 93. "Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*.

Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 204 - 94a. “Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus,” *Annual Book of ASTM Standards, Volume 04.01, Cement; Lime; Gypsum*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 231 - 91b. “Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 294 - 86 (1991). “Descriptive Nomenclature for Constituents of Natural Mineral Aggregates,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 295 - 90. “Guide for Petrographic Examination of Aggregates for Concrete,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 311 - 94b. “Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 469 - 94. “Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 534 - 94. “Specification for Preformed Flexible Elastomeric Cellular Thermal Insulation in Sheet and Tubular Form,” *Annual Book of ASTM Standards, Volume 04.06, Thermal Insulation; Environmental Acoustics*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 535 - 89. “Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 566 - 95. “Test Method for Total Moisture Content of Aggregate by Drying,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 618 - 95. “Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 845 - 90. “Specification for Expansive Hydraulic Cement,” *Annual Book of ASTM Standards, Volume 04.01, Cement; Lime; Gypsum*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 1064 - 86 (1993). “Test Method for Temperature of Freshly Mixed Portland Cement Concrete,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM C 1077 - 95a. “Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation,” *Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 1556 - 90. “Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method,” *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 2167 - 94. “Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method,” *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 2216 - 92. "Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 2922 - 91. "Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 3017 - 88 (1993). "Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM D 4791 - 95. "Test Method for Flat or Elongated Particles in Coarse Aggregate," *Annual Book of ASTM Standards, Volume 04.03, Road and Paving Materials; Pavement Management Technologies*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

ASTM E 534 - 91. "Test Methods for Chemical Analysis of Sodium Chloride," *Annual Book of ASTM Standards, Volume 15.05, Engine Coolants; Halogenated Organic Solvents; Industrial Chemicals*. Philadelphia, PA: American Society for Testing and Materials. (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187, 215/299-5400.)

Brodsky, N.S., F.D. Hansen, and T.W. Pfeifle. 1996. "Properties of Dynamically Compacted WIPP Salt," *4th International Conference on the Mechanical Behavior of Salt, Montreal, Quebec, June 17-18, 1996*. SAND96-0838C. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Technical Library, Sandia National Laboratories, Albuquerque, NM.)

Brown, E.R. 1990. "Density of Asphalt Concrete--How Much is Needed?," *Transportation Research Record No. 1282*. Washington, DC: Transportation Research Board. 27-32. (Copy on file in the SWCF.)

Callahan, G.D., M.C. Loken, L.D. Hurtado, and F.D. Hansen. 1996. "Evaluation of Constitutive Models for Crushed Salt," *4th International Conference on the Mechanical Behavior of Salt, Montreal, Quebec, June 17-18, 1996*. SAND96-0791C. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the SWCF as WPO36449.)

Cheung, S.C.H., M.N. Gray, and D.A. Dixon. 1987. "Hydraulic and Ionic Diffusion Properties of Bentonite-Sand Buffer Materials," *Coupled Processes Associated with Nuclear Waste*

Repositories, Proceedings of the International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, CA, September 18-20, 1985. Ed. C-F. Tsang. Orlando, FL: Academic Press, Inc. 383-407. (Copy on file in the SWCF.)

CRD-C 38 - 73. "Method of Test for Temperature Rise in Concrete," *Handbook for Concrete and Cement*. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station. (Copy on file in the SWCF as WPO39656.)

DOE (U.S. Department of Energy). 1995. *Waste Isolation Pilot Plant Sealing System Design Report*. DOE/WIPP-95-3117. Carlsbad, NM: U.S. Department of Energy, Waste Isolation Pilot Plant. (Copy on file in the SWCF as WPO29062.)

EPA (Environmental Protection Agency). 1996a. *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations. Response to Comments Document for 40 CFR Part 194*. EPA 402-R-96-001. Washington, DC: Environmental Protection Agency, Office of Radiation and Indoor Air. (Copy on file in the Nuclear Waste Management Library, Sandia National Laboratories, Albuquerque, NM.)

EPA (Environmental Protection Agency). 1996b. *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations. Background Information Document for 40 CFR Part 194*. EPA 402-R-96-002. Washington, DC: Environmental Protection Agency, Office of Radiation and Indoor Air. (Copy on file in the Nuclear Waste Management Library, Sandia National Laboratories, Albuquerque, NM.)

Freeman, H.D., and R.A. Romine. 1994. *Hanford Permanent Isolation Barrier Program: Asphalt Technology Test Plan*. PNL-9336. Richland, WA: Pacific Northwest Laboratories. (Copy available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA, 22161, 703/487-4650. Order number: DE94013454.)

Gray, M.N. 1993. *OECD/NEA International Stripa Project. Overview Volume III: Engineered Barriers*. Stockholm, Sweden: SKB, Swedish Nuclear Fuel and Waste Management Company. (Copy on file in the Nuclear Waste Management Library, Sandia National Laboratories, Albuquerque, NM as TD898.2 .G73 1993.)

Hansen, F.D., and E.H. Ahrens. 1996. "Large-Scale Dynamic Compaction of Natural Salt," *4th International Conference on the Mechanical Behavior of Salt, Montreal, Quebec, June 17-18, 1996*. SAND96-0792C. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the SWCF as WPO39544.)

IAEA (International Atomic Energy Agency). 1990. *Sealing of Underground Repositories for Radioactive Wastes*. STI/DOC/10/319. Technical Reports Series No. 319. Vienna, Austria: International Atomic Energy Agency; Lanham, MD: Unipub. (Copies on file at the Technical

Library, Sandia National Laboratories, Albuquerque, NM and at Centennial Science and Engineering Library, University of New Mexico, Albuquerque, NM.)

Kjartanson, B.H., N.A. Chandler, A.W.L. Wan, C.L. Kohle, and P.J. Roach. 1992. "Use of a Method Specification for In Situ Compaction of Clay-Based Barrier Materials," *High Level Radioactive Waste Management, Proceedings of the Third International Conference, Las Vegas, NV, April 12-16, 1992*. La Grange Park, IL: American Nuclear Society, Inc.; New York, NY: American Society of Civil Engineers. Vol. 1, 1129-1136. (Copy on file in the SWCF.)

Knowles, M.K., and C.L. Howard. 1996. "Field and Laboratory Testing of Seal Materials Proposed for the Waste Isolation Pilot Plant," *Proceedings of the Waste Management 1996 Symposium, Tucson, AZ, February 25-29, 1996*. SAND95-2082C. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the SWCF as WPO30945.)

Mitchell, J.K. 1993. *Fundamentals of Soil Behavior*. 2nd ed. New York, NY: John Wiley & Sons, Inc.

Myers, D.R., and D.A. Duranceau. 1994. *Prototype Hanford Surface Barrier: Design Basis Document*. BHI-00007, Rev. 00. Richland, WA: Bechtel Hanford, Inc. for the U.S. Department of Energy, Office of Environmental Restoration and Waste Management. (Copy on file at the Nuclear Waste Management Library, Sandia National Laboratories, Albuquerque, NM.)

Nilsson, J. 1985. "Field Compaction of Bentonite-Based Backfilling," *Engineering Geology*. Vol. 21, no. 3-4, 367-376. (Copy on file in the SWCF.)

Onofrei, M., M.N. Gray, W.E. Coons, and S.R. Alcorn. 1992. "High Performance Cement-Based Grouts for Use in a Nuclear Waste Disposal Facility," *Waste Management*. Vol. 12, no. 2/3, 133-154. (Copy on file in the SWCF.)

Pfeifle, T.W., F.D. Hansen, and M.K. Knowles. 1996. "Salt-Saturated Concrete Strength and Permeability," *4th Materials Engineering Conference, ASCE Materials Engineering Division, Washington, DC, November 11-18, 1996.* Albuquerque, NM: Sandia National Laboratories.)

Pusch, R. 1982. "Mineral-Water Interactions and Their Influence on the Physical Behavior of Highly Compacted Na Bentonite," *Canadian Geotechnical Journal*. Vol. 19, no. 3, 381-387. (Copy on file in the SWCF.)

Pusch, R., and L. Börgesson. 1989. "Bentonite Sealing of Rock Excavations," *Sealing of Radioactive Waste Repositories, Proceedings of an NEA/CEC Workshop, Braunschweig, Germany, May 22-25, 1989*. EUR 12298. Paris: Organisation for Economic Co-Operation and Development. 297-308. (Copy on file in the SWCF.)

Pusch, R., M. Gray, F. Huertas, M. Jorda, A. Barbreau, and R. Andre-Jehan. 1989. "Sealing of Radioactive Waste Repositories in Crystalline Rock," *Sealing of Radioactive Waste Repositories, Proceedings of an NEA/CEC Workshop, Braunschweig, Germany, May 22-25, 1989*. EUR

12298. Paris: Organisation for Economic Co-Operation and Development. 214-228. (Copy on file in the SWCF.)

Wakeley, L.D., P.T. Harrington, and F.D. Hansen. 1995. *Variability in Properties of Salado Mass Concrete*. SAND94-1495. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the SWCF as WPO22744.)

Wing, N.R., and G.W. Gee. 1994. "Quest for the Perfect Cap," *Civil Engineering*. Vol. 64, no. 10, 38-41. (Copy on file in the SWCF as WPO21158.)

(This page intentionally blank)

FIGURES

(This page intentionally blank)

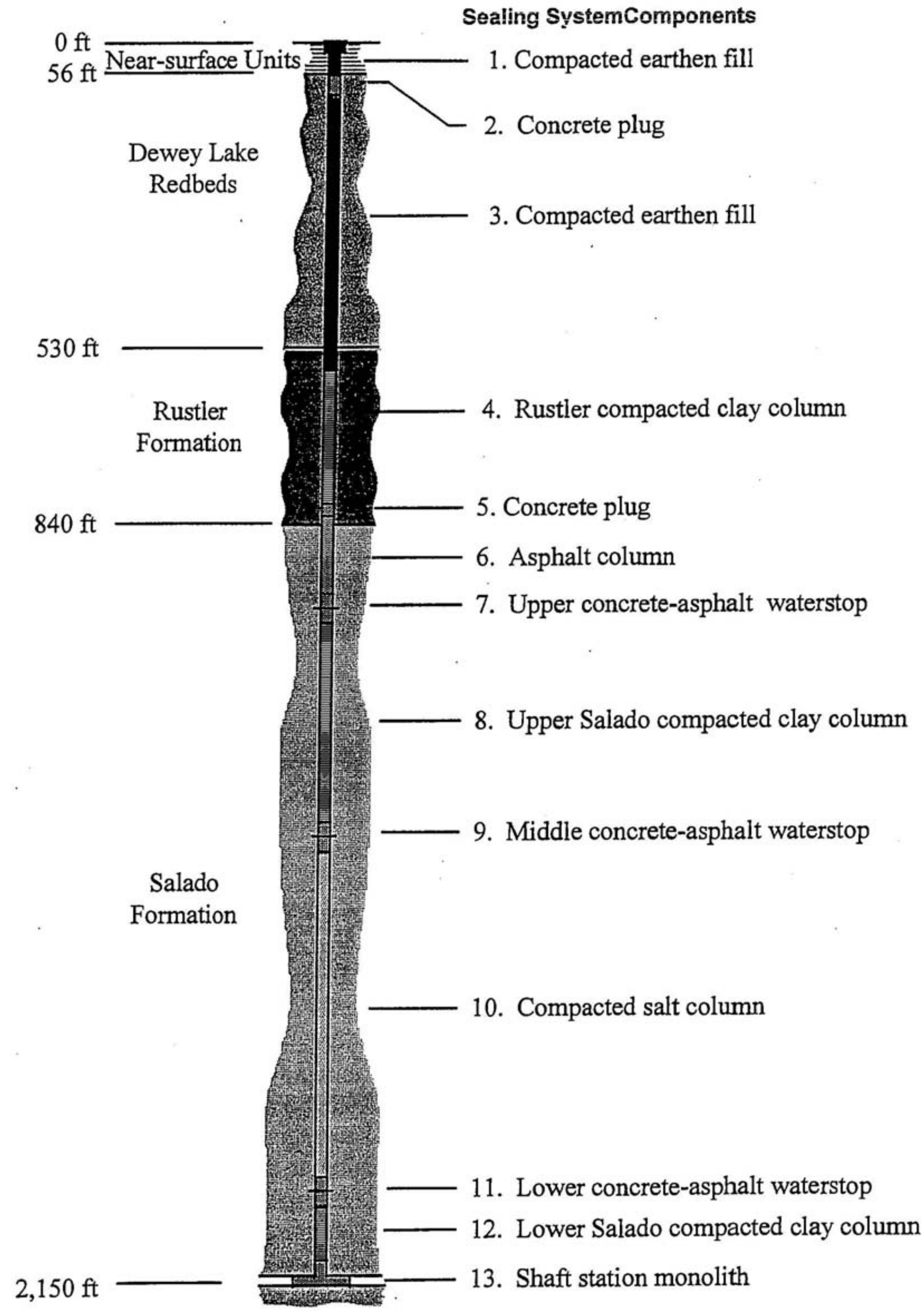

Figure I2A-1
Schematic of the WIPP shaft seal design

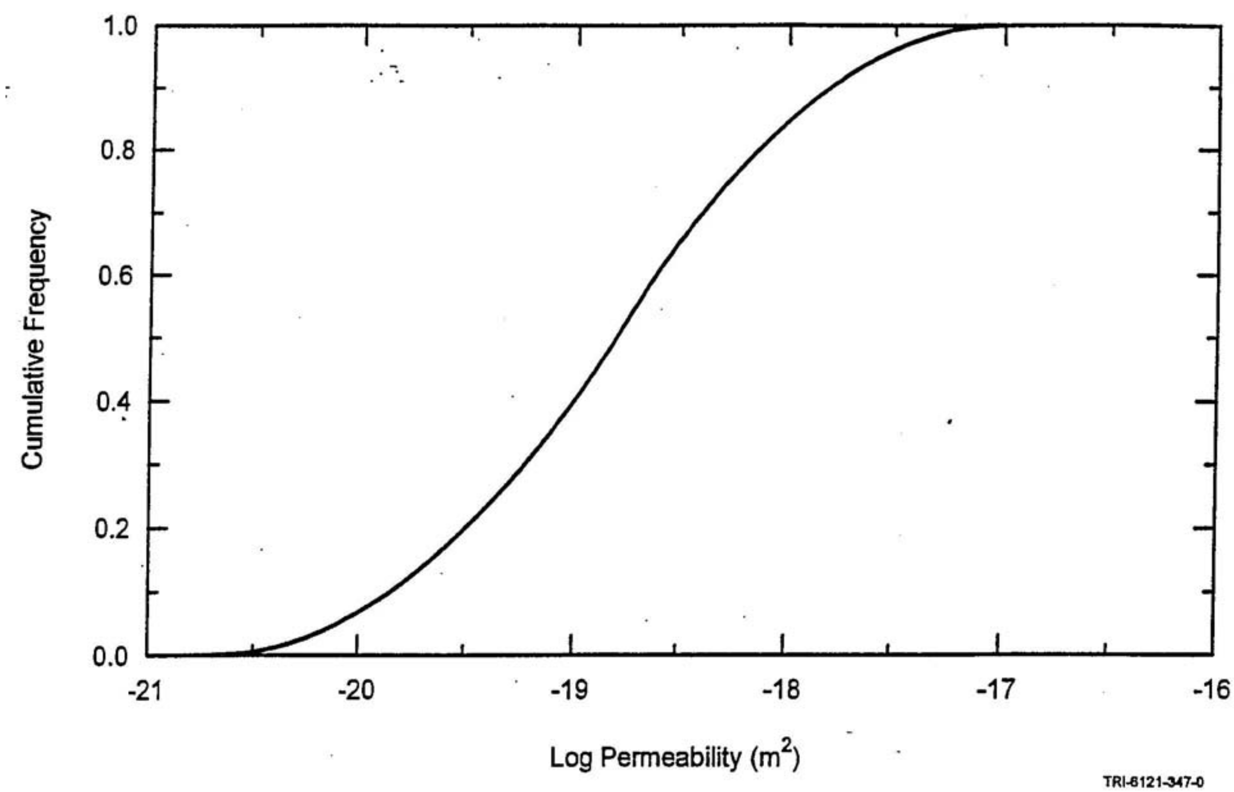

Figure I2A-2
Cumulative distribution function for SMC

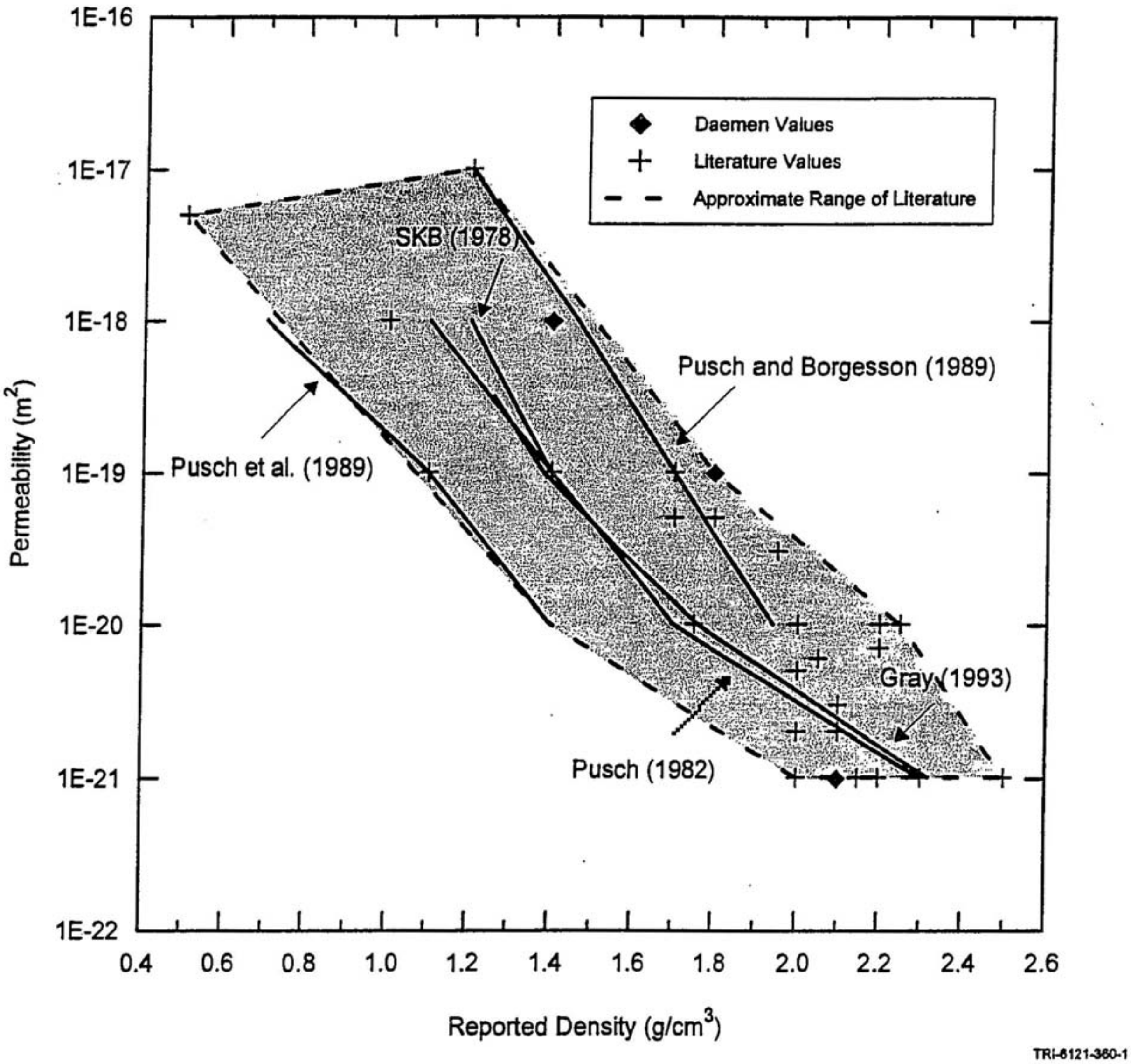

Figure I2A-3
Sodium bentonite permeability versus density

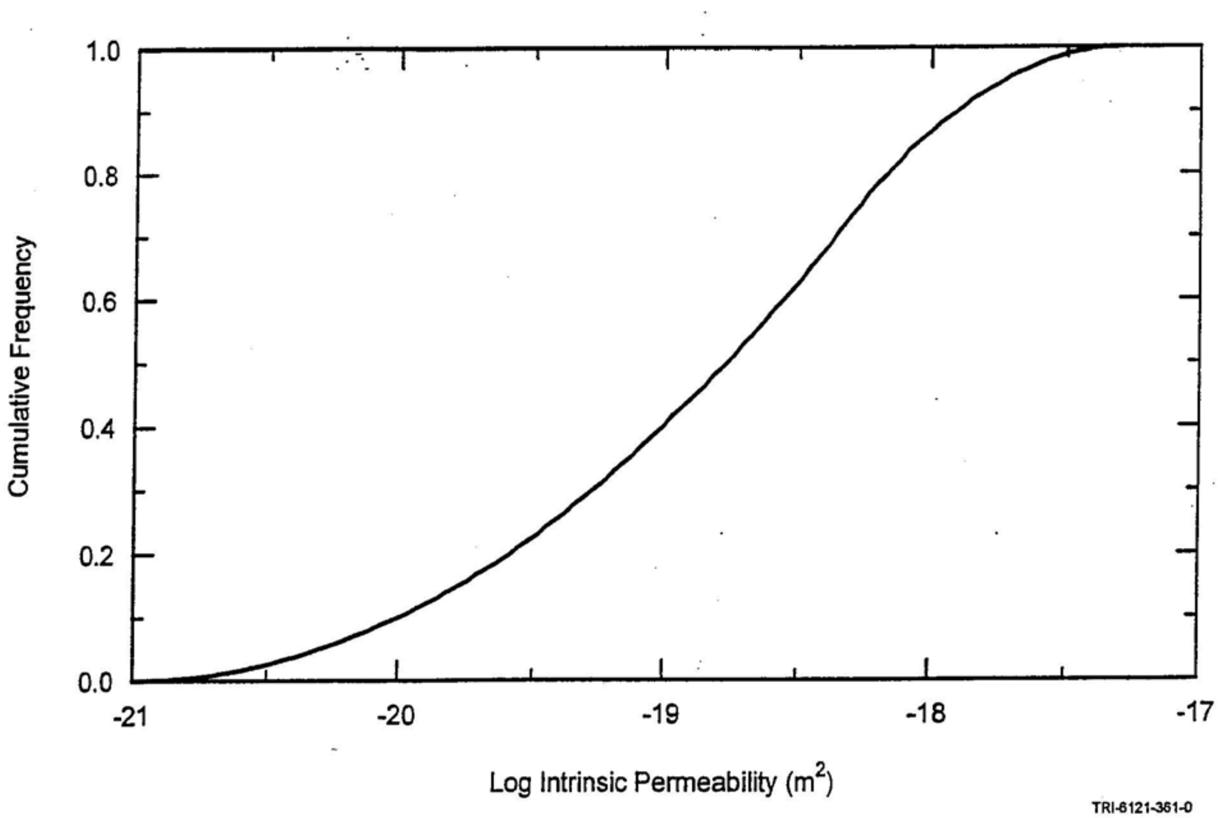

Figure I2A-4
Cumulative frequency distribution for compacted bentonite

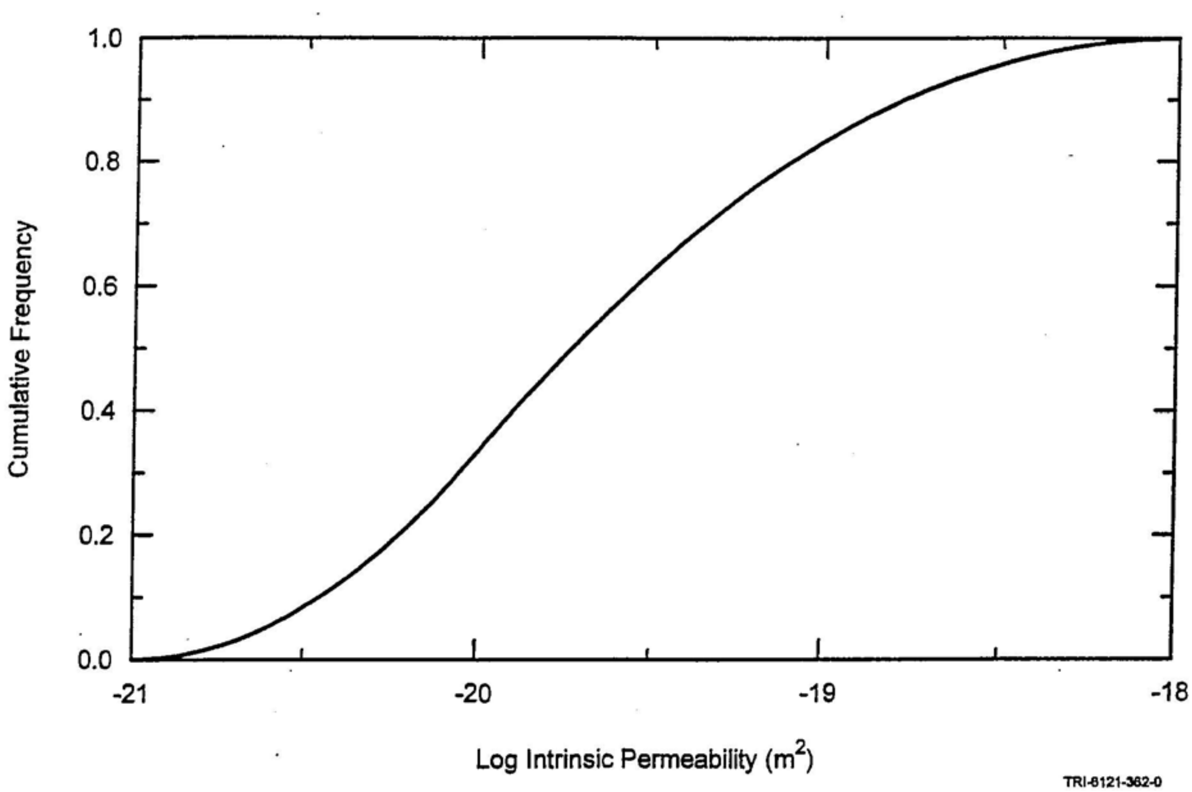

Figure I2A-5
Asphalt permeability cumulative frequency distribution function

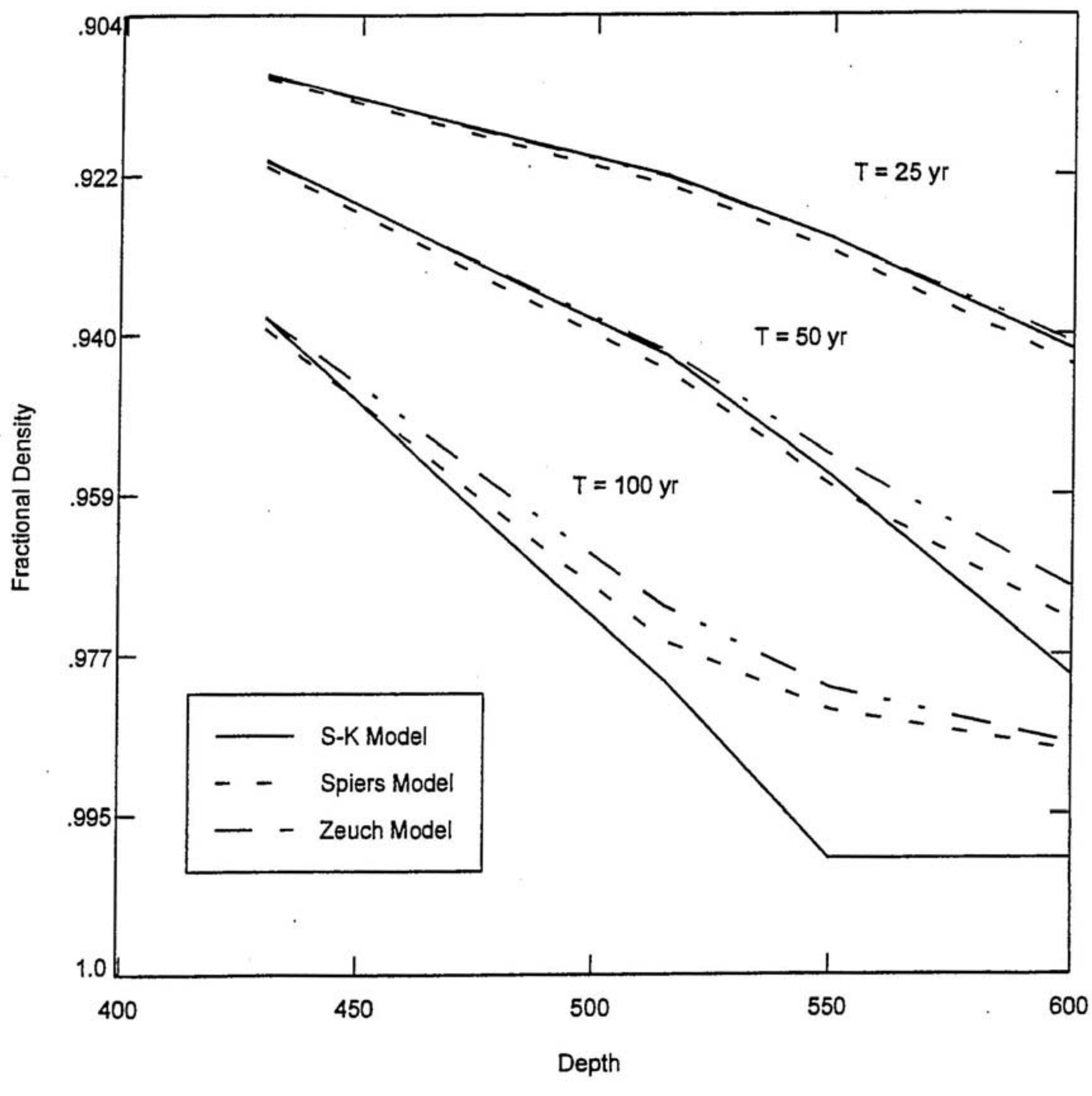

Figure I2A-6
Fractional density of the consolidating salt column

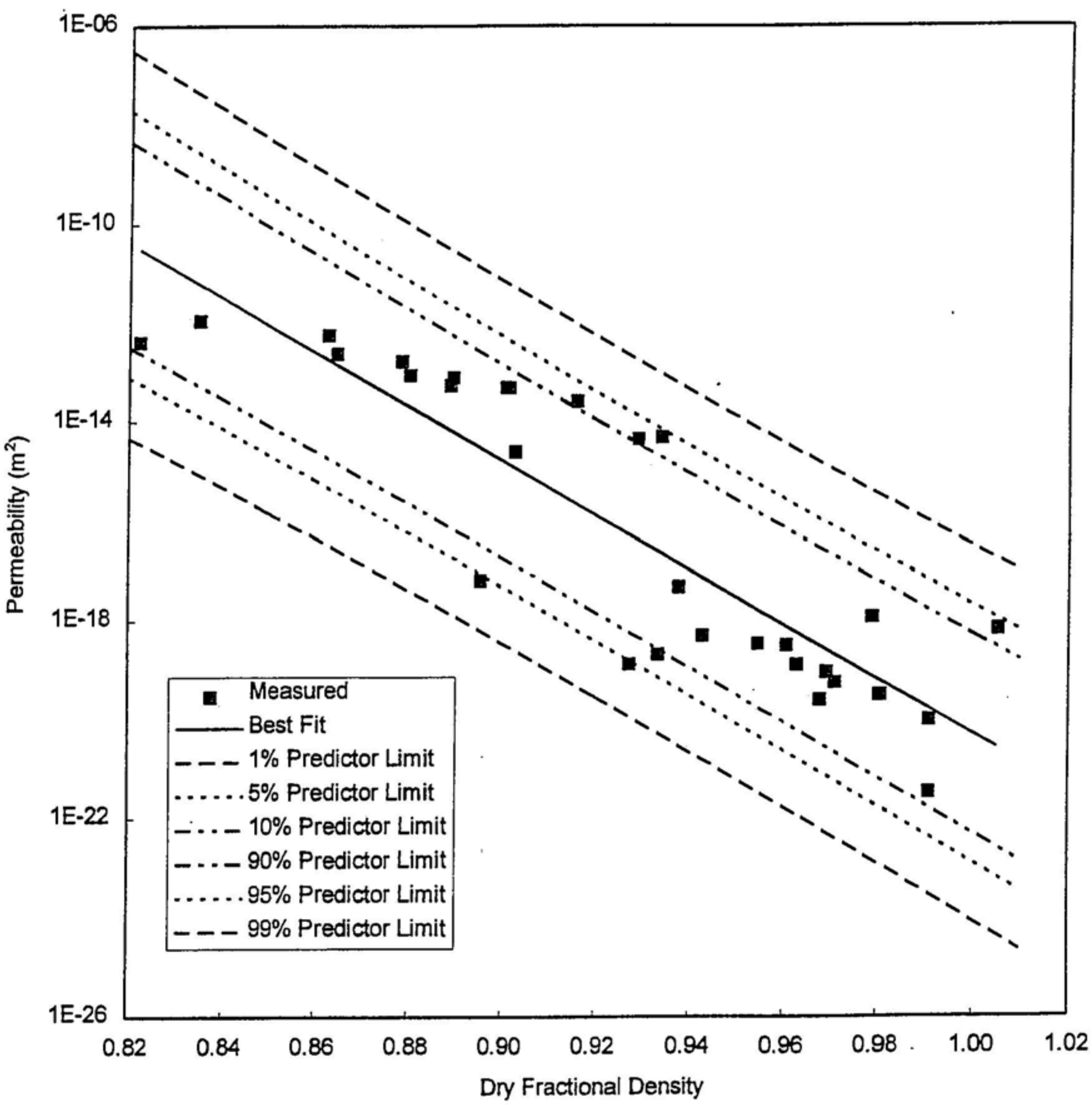

Figure I2A-7
Permeability of consolidated crushed salt as a function of fractional density

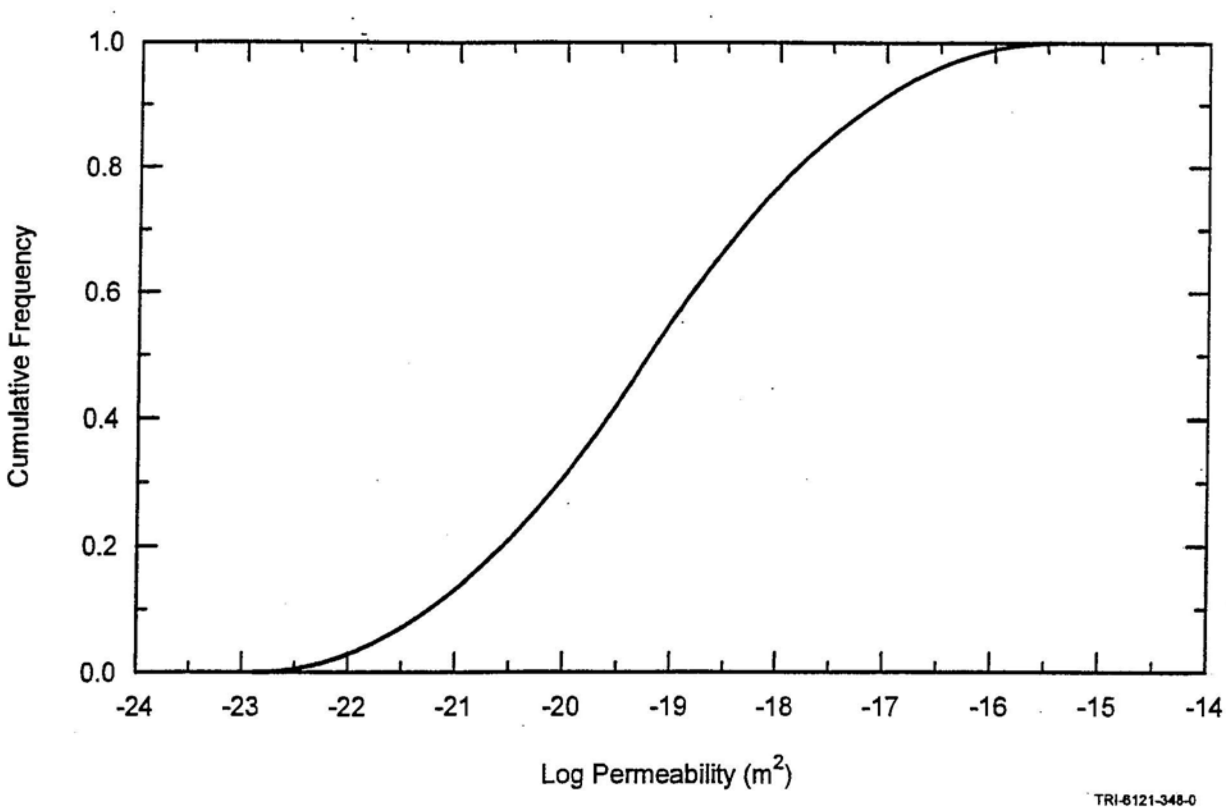

Figure I2A-8
Compacted salt column permeability cumulative frequency distribution function at seal midpoint 100 years following closure