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# A SHAFT SEAL SYSTEM FOR THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

As part of the demonstration of compliance with federal regulations, a shaft seal system has been designed for the Waste Isolation Pilot Plant. The system completely fills the 650-m shafts with components consisting of the common engineering materials, each of which possesses low permeability, longevity, and can be constructed using available technology. Design investigations couple rock mechanics and fluid flow analysis and tests of these materials within the natural geological setting, and demonstrate the effectiveness of the design.


## I. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), near Carlsbad, New Mexico, is designed as a mined geologic repository for the disposal of transuranic (TRU) radioactive wastes generated by DOE defense programs. Before accepting waste, the DOE is required to evaluate the repository against the applicable regulatory criteria (40 *CFR* Part 191 and Part 194), and the EPA must certify that compliance has been satisfactorily demonstrated. A shaft seal system design is an integral part of this demonstration of compliance with the governing regulations and meets the requirements for engineered barriers that limit entry of water into the site and potential escape of contaminants beyond regulated levels. The design represents a culmination of several years of effort, including laboratory and field testing[1] and design and analysis activities.[2] These efforts have led to a well-documented design that provides assurance that such a shaft seal system can be constructed using available materials and methods, and will perform as designed.

The purpose of the shaft seal system is to limit fluid flow within four existing shafts after the WIPP is decommissioned. Within each shaft the requirement is to mitigate the potential fluid transport paths along the opening itself, along the interface between the seal material and the host rock, and within the disturbed rock surrounding the opening. The seal system will not be implemented for several decades, but to establish that regulatory compliance can be achieved at that future date, a shaft seal system has been designed that possesses excellent durability and performance, and that can be constructed using existing technology. The design approach is conservative, reducing uncertainty in long-term performance through the use of redundant functional elements and multiple common materials. It is recognized that changes in the design described here will occur before construction, and that this design is not the only possible combination of materials and construction strategies that could adequately limit fluid flow within the shafts. However, this system could be constructed today, if required, and would perform as required for the regulatory period of 10,000 years.

## II. SITE SETTING

The WIPP is located in southeast New Mexico at a depth of 650 m in a bedded sequence of evaporites. The repository is situated in the Salado Formation and is overlain by 400 m of very low permeability bedded evaporites, which have intrinsically small water-bearing capacity. The Rustler Formation, overlying the Salado, contains the primary source of groundwater in the vicinity of the WIPP: a 24-m dolomite called the Culebra Member. Minor groundwater has been measured in the Magenta Member of the Rustler Formation. Formations above the Salado consist of approximately 250 m of flat-lying sedimentary lithologies, including anhydrite, claystone, siltstone, and sandstone. The Salado Formation itself consists primarily of salt, which is highly plastic and exhibits time-dependent deformation, or creep. This property of the Salado ensures that continuous fractures will not exist, fractures near excavations will heal over time, and shaft seal components will be tightly contained by creep of the shaft walls.

## III. DESIGN GUIDANCE

Use of both engineered and natural barriers to isolate wastes from the accessible environment is required by 40 *CFR* 191.14(d), and the use of engineered barriers to prevent or substantially delay movement of water or radionuclides toward the accessible environment is required by 40 *CFR* 194.44. Quantitative requirements for potential releases of hazardous constituents from the repository system are specified in 40 *CFR* 191; however, the regulations impose these quantitative release requirements on the total repository system, not on individual subsystems of the repository, such as the shaft sealing subsystem.

Design guidance for the shaft seal system addresses the need for the WIPP to comply with these system requirements and to follow accepted engineering practices using demonstrated technology. This design guidance includes the items covered below:

- limit hazardous constituents reaching regulatory boundaries,
- restrict groundwater flow through the sealing system,
- use sound engineering materials possessing long-term stability,
- protect against structural failure of system components,
- minimize subsidence and prevent accidental entry, and
- utilize available construction methods and materials.

The design has been developed to respond to these qualitative design guidelines, and is supported by extensive field and laboratory testing and analyses. The design philosophy is based on reducing the uncertainty associated with any particular element by using multiple sealing system components and by using components that are constructed from different materials.

## IV. DESIGN DESCRIPTION

The shaft sealing system, shown schematically in Figure 1, consists of 13 elements that completely fill the shaft with engineered materials possessing high density and low permeability. The Salado Formation components provide the primary barrier by permanently limiting fluid transport along the shaft. Components within the Rustler Formation limit commingling between brine-bearing members. Components from the Rustler to the surface fill the shaft with common materials of high density, consistent with good engineering practice, but does not affect regulatory compliance considerations. The various types of components are briefly described below, from the bottom of the shaft upward.

### A. Shaft Station Monolith

At the bottom of each shaft, a concrete monolith supports the local roof. This is to be constructed using a salt-saturated concrete, called Salado Mass Concrete (SMC), which has been tailored to match site conditions.[3] The salt-handling shaft and the waste-handling shaft have sumps which will also be filled with salt-saturated concrete as part of the monolith. The concrete will be placed using a slickline from the surface

### B. Clay Columns

A commercial-grade sodium bentonite, commonly used for sealing wells, is specified for the compacted clay components in the Salado and Rustler Formations. Clay columns will have a permeability on the order of $10^{-18}$ $m^2$ and a total length of more than 150 m. This combination of permeability and length will effectively limit brine movement from the time the columns are placed, providing an effective barrier to fluid migration throughout the 10,000-year regulatory period and thereafter. Locations of the Salado clay columns are selected to limit brine and potential gas migration into the consolidating salt column. In addition to sealing the shaft cross-section, the clay will be sufficiently stiff[2] to promote healing of fractures in the surrounding rock salt near the bottom of the shafts. This healing limits or eliminates the potential for significant flow of gases or brines through the DRZ. The Rustler clay column limits brine communication between the Magenta and Culebra Members of the Rustler Formation. Current construction specifications call for these three seal components to be placed as compressed blocks, although dynamic compaction has demonstrated potential as an alternative construction method.

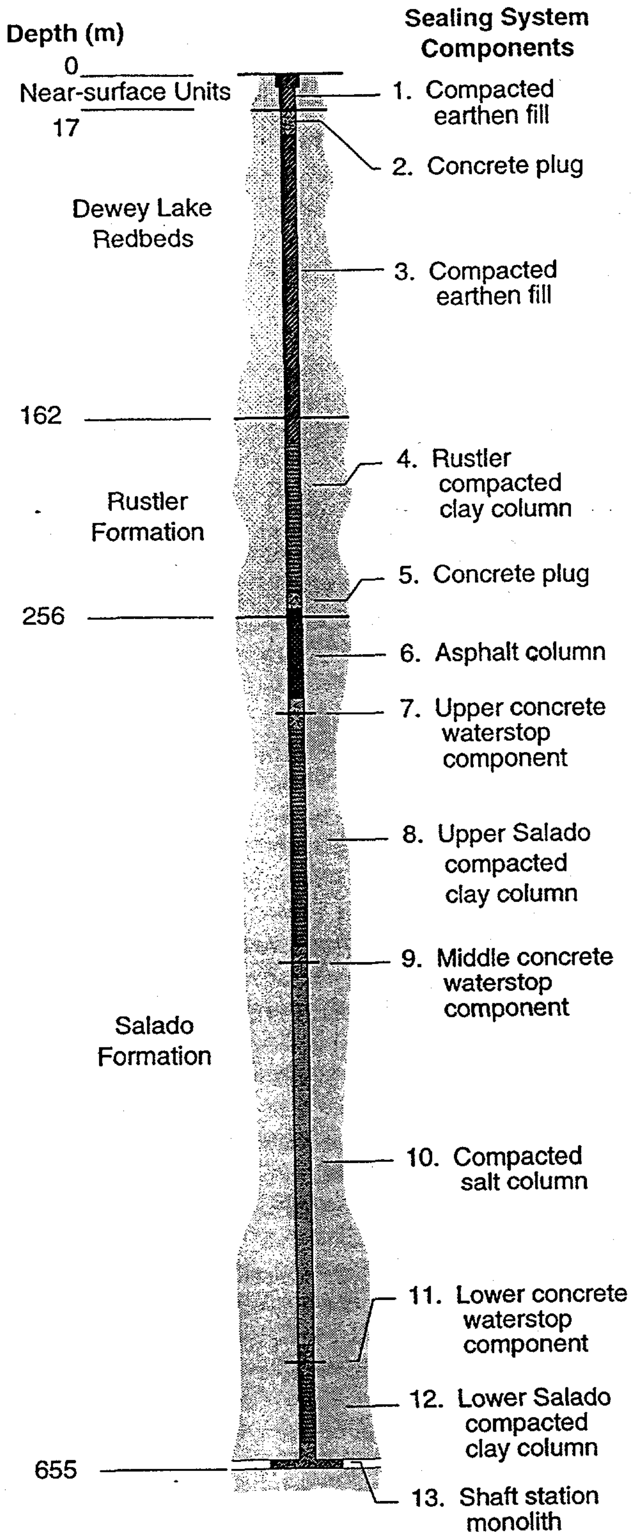


Figure 1. Schematic of the Air Intake Shaft Sealing System

C. Concrete-Asphalt Waterstop Components

Concrete-asphalt waterstop components include three elements: an upper concrete plug, a central asphalt waterstop, and a lower concrete plug. Three such components are located within the Salado Formation. These concrete-asphalt waterstop components provide independent shaft cross section and DRZ seals that limit fluid transport—either brine from above or brine/gas transport from the repository level. Concrete will fill irregularities in the shaft wall and the use of the salt-saturated concrete ensures good bonding with salt and a rapid sealing of the interface. Salt creep against the rigid concrete components establishes a compressive stress state and promotes early healing of the salt DRZ surrounding the concrete plugs. The asphalt intersects the shaft cross section and the DRZ. The concrete will be emplaced using a slickline; asphalt will be emplaced with a heated slickline.

D. Compacted Salt Column

Each shaft seal includes a long column of dynamically compacted Salado salt with 1.5 wt% water added during construction. This column will be a primary long-term seal element. Construction demonstrations have shown that mine-run WIPP salt can be dynamically compacted to a density equivalent to approximately 90% of the average density of intact Salado salt.[4] Over time, creep closure will consolidate the crushed salt further, with a fractional density of at least 97% being anticipated within 100 years. This density will result in an effective permeability[5] for the salt column of at least $5 \times 10^{-19}$ m$^2$. The location of the compacted salt column near the bottom of the shaft ensures the fastest achievable consolidation of the compacted salt column after closure of the repository.

E. Asphalt Column

An asphalt-aggregate mixture is specified for the asphalt column, which bridges the Rustler/Salado contact and provides an essentially impermeable seal for the shaft cross section and the shaft wall interface. Asphalt is placed with a heated slickline.

F. Concrete Plugs

A concrete plug is located just above the asphalt column and keyed into the surrounding rock. The plug permits work to begin on the overlying clay column before the asphalt has completely cooled. Another concrete plug is located near the surface, extending downward from the top of the Dewey Lake Redbeds.

G. Earthen Fill

The upper shaft is filled with locally available compacted earthen fill. Most of the fill is dynamically compacted (the same method used to construct the salt column) to a density approximating the surrounding materials. The uppermost earthen fill is compacted with a sheepsfoot roller or vibratory plate compactor.

## V. STRUCTURAL ANALYSES

A number of structural calculations have been performed as part of the design process. These generally have addressed one or more of the following concerns:

1. Stability of the components, including:
   - potential for thermal cracking of concrete seals;
   - structural stability of seal components under loads resulting from creep of surrounding salt as well as the stability of other seal components affected by gravity or clay swelling, dynamic compaction, and potential repository-generated gas pressures;
   - shaft closure-induced consolidation of compacted salt seals.
2. Influences of structural response on the hydrological properties of the seal and surrounding rock, including:
   - spatial extent of the DRZ within the Salado salt formation surrounding the shafts as a function of depth, time, and seal material moduli;
   - fracturing and DRZ development within Salado Formation interbeds;
   - compacted salt fractional density as a function of depth and time;
   - impact of pore pressures on consolidation of compacted-salt seals.
3. Construction methods:
   - emplacement and structural performance of asphalt waterstops;
   - potential effects of backfilling shaft stations.

Perhaps the most important and interesting calculations are those on the development and healing of the DRZ and on the consolidation of the crushed salt column. These are briefly described below.

A. DRZ Behavior

The development and subsequent healing of the DRZ that forms in the rock mass surrounding the WIPP shafts is a significant concern in the seal design, since this zone can present a preferred pathway for fluids. It is well known that a DRZ will develop in the rock adjacent to the shaft immediately after excavation. The presence of rigid components within the shaft will cause the DRZ within the salt to heal as the seal element restrains inward creep.

Three analyses have been performed to determine the behavior of the DRZ in the rock mass surrounding the shaft. The first analysis considers time-dependent DRZ development and subsequent healing in the Salado salt surrounding each of the four seal materials. All seal materials below a depth of about 300 m provide sufficient rigidity to heal the DRZ, a phenomenon that occurs quickly around rigid components near the shaft bottom. The second analysis considers time-dependent development of the DRZ within anhydrite and polyhalite interbeds within the Salado Formation. For all interbeds, the factor of safety against failure (shear or tensile fracturing) increases with depth into the rock surrounding the shaft wall. The results show that most marker beds remain intact, interrupting continuity of the DRZ throughout the Salado. This third analysis considers time-independent DRZ development within near-surface and Rustler formations. In that region, anhydrites and dolomites remain intact, while mudstones may fracture. DRZ in nonhalite rocks is not expected to heal. These results are used as input conditions for fluid flow analyses.

B. Compacted Salt Behavior

Crushed salt deforms under applied compression both elastically and by creep. The relevant properties for crushed WIPP salt have been obtained from extensive laboratory investigations and data analyses.[6] The progress of this consolidation has been modeled, as has the effect of pore pressure on consolidation. The structural calculation determines fractional density of the crushed-salt seal as a function of time and depth and uses the results to determine permeability.

## VI. HYDROLOGIC EVALUATIONS

The ability of the shaft seal system to satisfy design guidance is determined by the performance of the actual seal components within the physical setting where they are constructed. Hydrologic evaluations have focused on processes that could result in fluid flow through the shaft seal system and the ability of the seal system to limit this flow. Transport of radiological or hazardous constituents will be limited if the carrier fluids are similarly limited.

The physical processes that could affect seal system performance have been incorporated into four models, which are used to evaluate the design. These models evaluate: (1) downward migration of groundwater from the Rustler Formation; (2) gas migration and reconsolidation of the crushed salt seal component; (3) upward migration of brines from the repository; and (4) flow between water-bearing zones in the Rustler Formation. Results from the analyses are summarized below.

A. Downward Migration of Rustler Groundwater

The shaft seal system is designed to limit groundwater flowing into and through the shaft sealing system. The principal source of groundwater to the seal system is the Culebra Member of the Rustler Formation. Downward migration of Rustler groundwater is limited (1) to ensure that liquid saturation of the Salado salt column does not affect the consolidation process and (2) to limit quantities of brine reaching the repository horizon. Model results show that a maximum of approximately 17 $m^3$ of groundwater can migrate to the salt column. This volume does not significantly affect the reconsolidation process and is insignificant compared with the repository volume.

B. Fluid Migration/Salt Reconsolidation

A multiphase flow model of the lower seal system has been used to evaluate the performance of components extending from the middle concrete-asphalt waterstop component (located at the top of the salt column) to the repository horizon for 200 years following closure. During this time period, the principal fluid sources to the model consist of potential gas generated by the waste and lateral brine migration within the Salado Formation. The predicted downward migration of Rustler groundwater (discussed above) is included in this analysis. Model results predict that repository pressures as high as 14 MPa will not produce appreciable volumes of gas migration to the salt column over the 200-year simulation period. The relatively low gas flow is due to the low permeability and rapid healing of the DRZ around the lower concrete-asphalt component. The results plotted in Figure 2 show the effective permeability of the consolidating salt column as a function of time. The "base case" represents expected behavior, while the "continuous DRZ" represents a more conservative estimate. In either simulation, effective permeability within 100 years is less than $10^{-18}$ $m^2$, which will limit transport of brine or gas.

C. Upward Migration of Brine

Modeling results (discussed above) demonstrate that the crushed salt seal will reconsolidate to a very low permeability within 100 years following repository closure. Structural results show that the DRZ surrounding the long-term clay and crushed salt seal components will completely heal within the first several decades. As a result, migration of brine from the repository horizon through the sealed shafts will not occur over the regulatory period.

D. Intra-Rustler Flow

Based on estimated undisturbed and measured disturbed head differences between the various members of the Rustler Formation, nonhydrostatic conditions exist within the Rustler Formation. The relatively low undisturbed permeabilities of the mudstone and anhydrite units separating the Culebra and the Magenta naturally limit crossflow. However, the construction and subsequent closure of the shafts provide a potential permeable vertical conduit connecting water-bearing units. Calculations show that potential flow rates between the Culebra and the Magenta are insignificant. Under expected conditions, intra-Rustler flow is expected to be of such a limited quantity that (1) it will not affect either the hydraulic or chemical regime within the Culebra or the Magenta and (2) it will not be detrimental to the seal system itself.

## VII. CONCLUDING REMARKS

An effective, constructable shaft seal system has been designed for the WIPP. The application or adaptation of existing technologies for placement of seal components, combined with the use of available common materials, will ensure that the design can be constructed. Hydrologic evaluation of the sealing system shows very limited flows of gas or brine, while structural analyses ensure acceptable stress and deformation conditions and that seal materials function well in the environment in which they are placed. Confidence in these conclusions is bolstered by the basic design approach of using multiple components to perform each sealing function and by using extensive lengths within the shafts to effect a sealing system. The shaft seal system meets design requirements, can be constructed, and is supported with a substantial database.

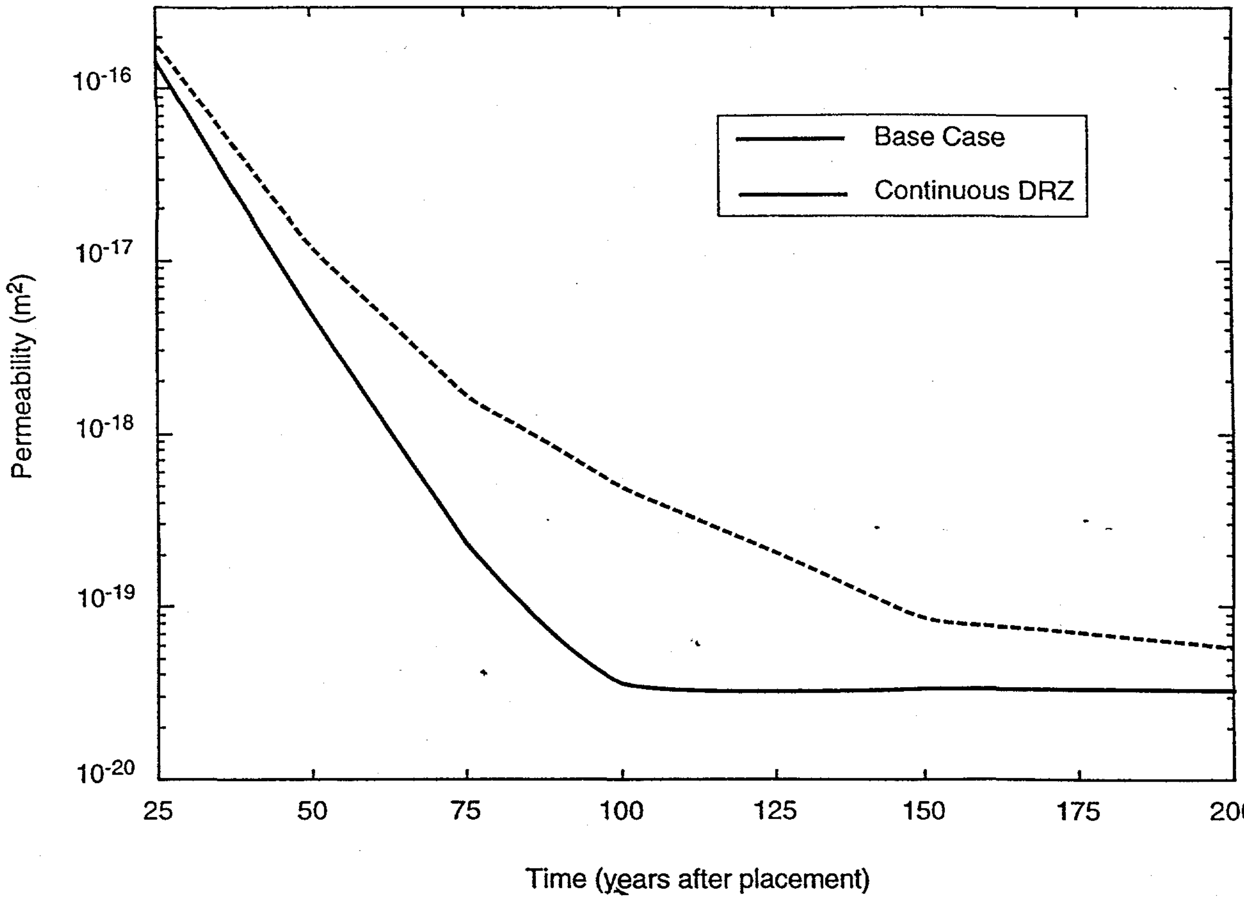


Figure 2. Effective Salt Column Permeability.


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