

KEY GEOMECHANICS ISSUES AT THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

Mechanical and hydrological properties of rock salt provide excellent bases for geological isolation of hazardous materials. Regulatory compliance determinations for the Waste Isolation Pilot Plant (WIPP) stand as testament to the widely held conclusion that salt provides excellent isolation properties. The WIPP saga began in the 1950s when the U.S. National Academy of Sciences (NAS) recommended a salt vault as a promising solution to the national problem of nuclear waste disposal. For over 20 years, the scientific basis for the NAS recommendation has been fortified by Sandia National Laboratories through a series of large scale field tests and laboratory investigations of salt properties. These scientific investigations helped develop a comprehensive understanding of salt's deformational behavior over an applicable range of stresses and temperatures. Sophisticated constitutive modeling, validated through underground testing, provides the computational ability to model long-term behavior of repository configurations. In concert with advancement of the mechanical models, fluid flow measurements showed not only that the evaporite lithology was essentially impermeable but that the WIPP setting was hydrologically inactive. Favorable mechanical properties ensure isolation of materials placed in a salt geological setting. Key areas of the geomechanics investigations leading to the certification of WIPP are *in situ* experiments, laboratory tests, and shaft seal design.

INTRODUCTION

The WIPP facility, as certified on 13 May 1998 by the U.S. Environmental Protection Agency (EPA), has evolved in scope and mission. Initially the concept facility was to house defense-related high level waste and transuranic waste in a two-tiered mine layout. Therefore, early field and laboratory testing investigated thermal effects in concert with ambient experiments to quantify deformational properties of salt. In a companion paper in these proceedings, a broad overview of the WIPP rock mechanics experimental programs is presented (1). Whereas the scope and results of the many tests (thousands of laboratory tests, and tens of underground experiments) are too sweeping to be captured in a single ten-page paper, primary and representative results will be presented here. This paper emphasizes three activities that highlight the comprehensive geomechanics program completed at the WIPP: 1) *In Situ* Experiments, 2) Laboratory Tests, and 3) Shaft Seal Design. In presenting the WIPP geomechanics program elements in this manner, one can appreciate the level of detail and sophistication employed by the U.S. Department of Energy (DOE) in its quest to certify the site to regulators and to convince oversight committees of site acceptability. This paper was prepared by Sandia National Laboratories, a multi program laboratory operated by Lockheed Martin for the DOE. The paper highlights select geomechanics findings from Sandia's 24 years of involvement in the WIPP project.

The concept of isolating hazardous materials from the biosphere by deep geological disposal enjoys wide support in the scientific community. At the time of this writing, only the German and US programs are actively researching the use of rock salt as a primary isolation medium for radioactive waste. The fact that a significant portion of the world's inventory of natural gas, hydrocarbons, and other strategic energy resources are stored in salt caverns provides compelling evidence that structural and hydrological properties of salt are excellently suited for geologic storage and isolation. As other countries engage in site selection

for their specific waste isolation programs, salt formations may be identified as candidate media. This paper might provide useful geomechanics background information for salt repository selection and evaluation.

IN SITU EXPERIMENTS

Beginning in the mid-1980s, an extensive series of underground experiments was deployed at the WIPP in a test area located just north of the planned waste disposal panels (as shown in Fig. 1). For more than a decade, the response of the WIPP underground was evaluated by these scientific experiments. Full-scale room experiments examined creep induced by mining, disturbed rock zone development, thermally driven response, waste package performance, and plugging/sealing techniques (2). Primary *in situ* experiments involving rock mechanics included:

- Thermal/Structural Interactions,
- Defense High Level Waste Mockup,
- Defense High Level Waste Overtest,
- Heated Axisymmetric Pillar,
- Plugging and Sealing Tests,
- Waste Package Performance Tests.

Many smaller scale underground investigations, such as those pertaining to hydrology and seal materials, were also undertaken. Some of these are noted in the legend on Fig. 1. This section will expound on the *in situ* mechanical program by providing representative examples.

In situ testing was conducted in the WIPP underground at a depth of 655 m, giving rise to a principal vertical stress of 15 MPa, with large stress differences occurring because of geometrically induced stress concentrations. Continuous deformation tends to reduce stress differences from the moment of excavation until equilibrium is once again established. The initial mission for the WIPP included disposal of defense high level waste, which generates heat during radioactive decay, as well as the currently planned inventory of transuranic waste. Therefore the natural reaction of salt to creep under differential stress was accentuated by heating in several early underground experi-

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ments. Thermal/Structural Interaction (TSI) tests simulated defense high level wastes, verified preliminary designs, and evaluated structural properties. Primary results included rates of salt creep and room closure, heat transfer effects, and validity of predictive methods. Because predictive capabilities are fundamental to long-term assessment, an axially symmetric pillar was constructed and heated with blanket heaters to a surface temperature approaching 90°C. These results helped interpret scale and geometric effects on modeling salt deformation.

Mechanical closure predictions were validated against *in situ* test results. Figure 2 illustrates the typical level of agreement between underground test results and predicted closure rates. Notable in Fig. 2 is the ambient closure, which approached 200 mm in the year before heaters were activated. Similarly, unsupported WIPP disposal rooms closed about 25% in the ten years since excavation, as experienced by Room 7 of Panel 1. The initial acceleration of the creep rate monitored in Room B (Defense High Level Waste Overtest) ascends because a thermal loading was applied as part of the test. Later, creep closure and concurrent dilation accelerated the closure rate owing to fracture. Eventually, roof rock in these experiments decoupled and were allowed to fall. During disposal operations, safe roof conditions can be maintained for decades with minimal ground control measures.

Based on a tremendous amount of *in situ* data, an acceptable creep model (discussed subsequently) was validated. Modeling of the WIPP geomechanical response effectively replicates observed behavior. The model itself, consistent with *in situ* experiments, has been generalized to facilitate comparison between two-dimensional and three-dimensional calculations. This sweep of geomechanical underground experiments helped build a solid understanding of the structural response of a repository situated at depth in salt. In fact, the National Research Council concluded that time-dependent deformation of salt "is now understood well enough to allow reliable long-term calculation of salt deformation behavior as it relates to repository performance" (4).

LABORATORY GEOMECHANICS INVESTIGATIONS

Laboratory experimental programs were initiated during siting investigations. In the mid-1970s, cores from drill holes were mechanically tested in the laboratory. Preliminary engineering properties, such as strength and deformation, were well documented before the first shaft was sunk in 1981. Concurrent with siting of the WIPP, the DOE's Office of Civilian Radioactive Waste Management sought a similar geologic setting for spent fuel from civil nuclear power plants. It rapidly became clear to the technical community that laboratory test machinery had to be assembled for adequate long-term testing under repository-relevant conditions. In close cooperation with the West German (before reunification) researchers, laboratory enterprises addressing a wide range of geomechanical investigations were engaged. Applications during those years emphasized thermally driven creep properties, with test temperatures as high as 200°C. Under most stress and temperature regimes applicable to repository investigations, salt deformation is governed by dislocation processes.

An advanced constitutive model describes the total steady-state creep rate as a sum of three component rates, each dependent on a different fundamental mechanism. This constitutive model is expressed mathematically as follows:

$$\dot{\epsilon}_s = \sum_{i=1}^3 \dot{\epsilon}_{s_i} \quad (1)$$

where the individual steady-state rates of the three relevant mechanisms are given by:

$$\dot{\epsilon}_{s_1} = A_1 e^{-Q_1/RT} \left(\frac{\sigma}{\mu} \right)^{n_1} \quad (2)$$

$$\dot{\epsilon}_{s_2} = A_2 e^{-Q_2/RT} \left(\frac{\sigma}{\mu} \right)^{n_2} \quad (3)$$

$$\dot{\epsilon}_{s_3} = |H(\sigma - \sigma_0)| [B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT}] \sinh \left[\frac{q(\sigma - \sigma_0)}{\mu} \right] \quad (4)$$

where A and B are constants; Q is the activation energy; T is the absolute temperature; R is the universal gas constant; μ is the shear modulus; σ is the generalized stress; n is the stress component; q is the stress constant; σ_0 is the lower stress limit of the dislocation slip mechanism; and $|H|$ is the Heaviside step function with the argument $\sigma - \sigma_0$ [i.e., $H(\sigma - \sigma_0) = 0$ for $\sigma < \sigma_0$; 1 for $\sigma > \sigma_0$]. Transient creep strain is accommodated by either work hardening or recovery branches, which account for stress according to an evolutionary equation (5). This constitutive model has been used and validated extensively in WIPP-related experiments.

Thermally activated deformational mechanisms are represented by exponential expressions in the constitutive model. Optical and scanning electron microscopy have documented microprocesses operating over temperature and stress regimes relevant to nuclear waste repositories. Generally, small strains initiate dislocation multiplication. Glide along dodecahedral planes is readily activated. Small thermal activation allows cross slip of glide dislocations, whereas higher temperatures (e.g., 100°C) provide sufficient thermal activation to promote recovery processes. Photomicrographs of etched cleavage chips exemplify a relatively modest free dislocation substructure and beautifully polygonized subgrains of a highly deformed specimen (Fig. 3). Optical microscopy was used to examine hundreds of deformed structures. These fundamental studies provide the scientific proof that the constitutive model represents deformational mechanisms at the atomistic level.

In the scientific investigations leading to development and validation of a salt flow law, ambient behavior was also quantified. Most volumes of salt surrounding repositories, even those for heat-generating wastes, remain at or near ambient temperature. Laboratory research ranged from determination of rudimentary tensile and compressive strength properties and attendant "elastic" constants to various Lode angle testing using thin-walled hollow cylinders. With modest mean stress, dilation of

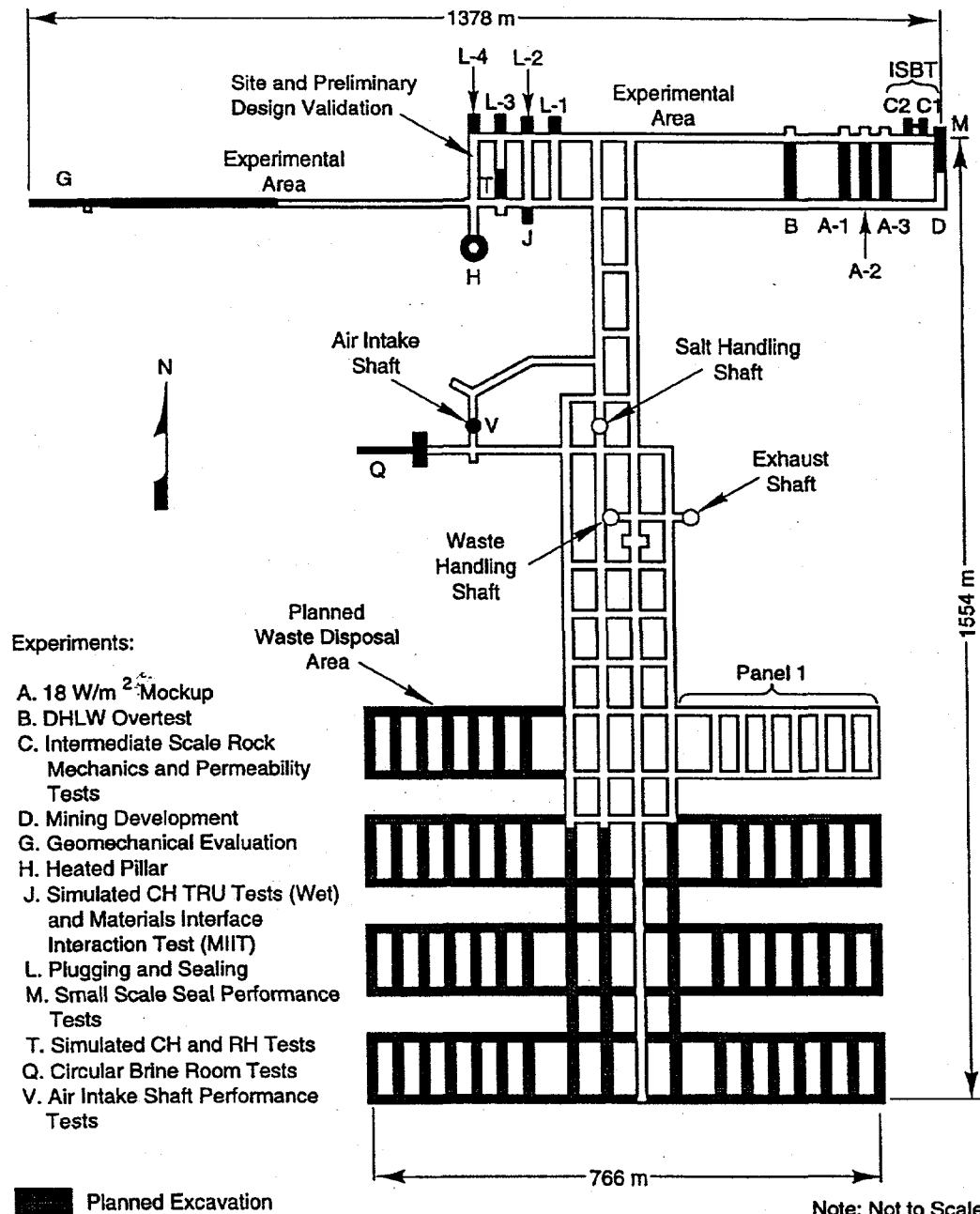


Fig. 1. Plan view of WIPP underground showing experimental area and projected disposal area.

salt is suppressed. The initiation of dilatancy and a functional relationship between volumetric strain and permeability are being investigated in current laboratory programs. Figure 4 is a representative photograph of salt deformed in the laboratory. Figure 5 plots typical lab test results, in this case strain as a function of constant mean stress.

Laboratory geomechanical research provides both basic and applied information. Basic phenomena, such as permeability as a function of damage or dislocation microprocesses, are applicable to mining, hydrocarbon storage, and waste repositories. Site-specific information helps quantify parameters for constitutive models and failure criteria directly applicable to WIPP evaluations. The laboratory investigations undertaken for WIPP applications provide useful information across the technical community.

SHAFT SEAL DESIGN AND ANALYSIS

Most geologically based repositories would provide ingress, egress, and ventilation through shafts, which provide direct linkage to the biosphere. At the WIPP, four shafts, ranging in diameter from 3.5 to 6.1 m, connect the disposal horizon to the surface. The shaft seal system provides an engineering barrier, as required by regulations. Decommissioning and abandonment surety depends on the ability to provide an engineered barrier within the shafts. The shaft seal system limits entry of formation water into the repository and restricts the release of fluids, which might carry contaminants. Shaft seals address fluid transport paths through the opening itself, along the interface between the seal material and the host rock, and within the disturbed rock surrounding the opening. The design approach applies redundancy to functional elements and specifies various common, low-permeability materials to reduce uncertainty in performance. The

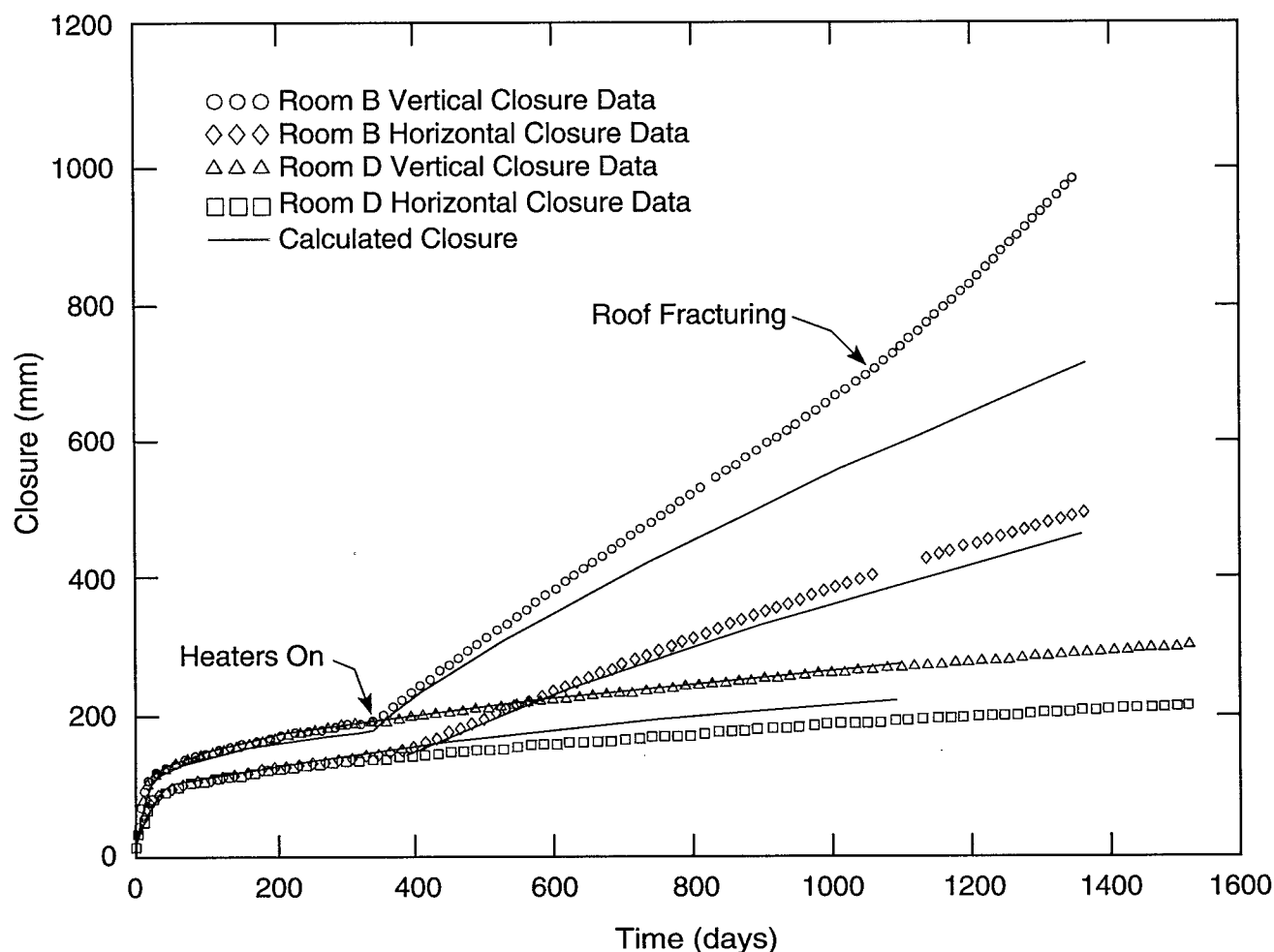


Fig. 2. Typical level of agreement between underground test results and predicted closure rates (3).

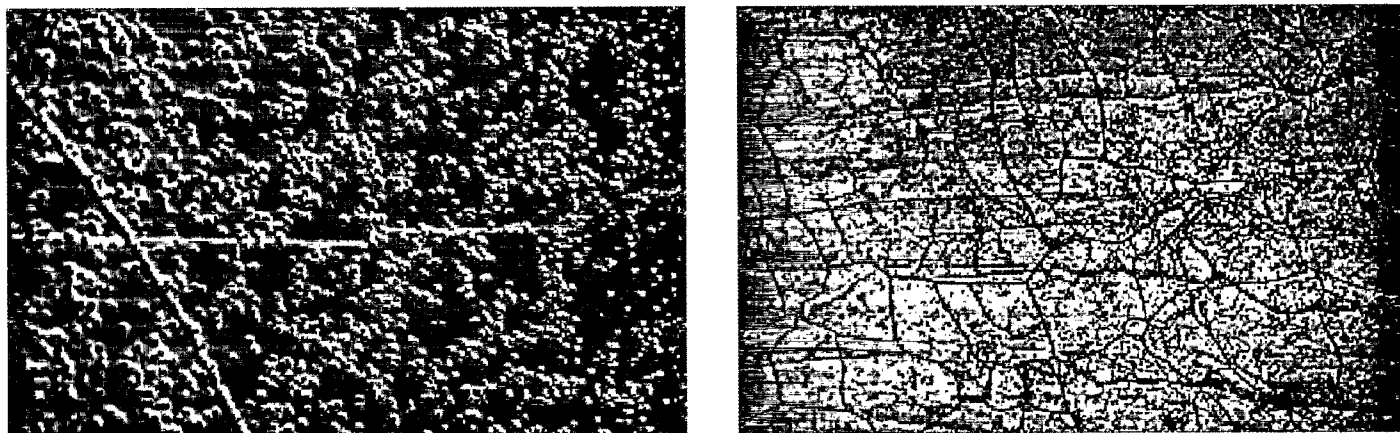


Fig. 3. Photomicrographs of etched cleavage chips.

design described here is very conservative and is likely to be modified before construction, and this design is not the only possible combination of materials and construction strategies that would adequately limit fluid flow within the shafts.

As illustrated in Fig. 6, the system comprises 13 elements that completely fill the shafts with engineered materials possessing high density and low permeability. To reduce the impact of system uncertainties and to assure a robust system, numerous

components comprise this sealing system. Materials used to form the shaft seals are commensurate with those identified in the scientific and engineering literature as appropriate for sealing mines and deep geologic repositories for radioactive wastes. Components include long columns of clay, densely compacted crushed salt, a waterstop of asphaltic material sandwiched between massive low-permeability concrete plugs, a column of asphalt, and a column of earthen fill. Different materials perform

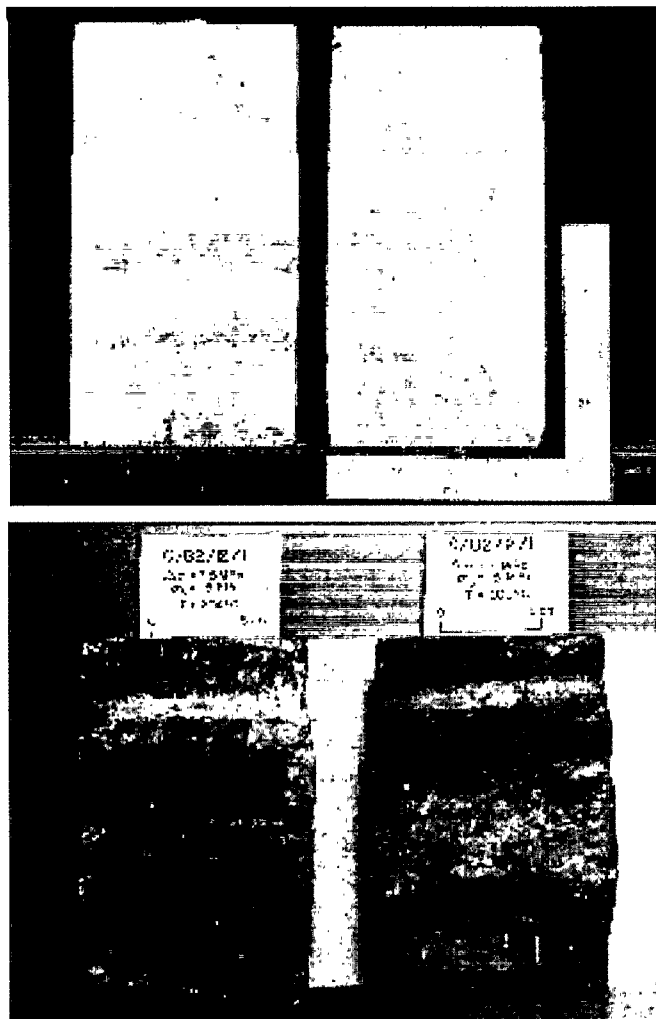


Fig. 4. Representative photographs of salt deformed in the Laboratory.

identical functions within the design, thereby adding confidence in the system performance through redundancy. Laboratory and field measurements of component properties and performance provide the basis for the design and related evaluations. Hydrological, mechanical, thermal, and physical features of the system are evaluated in a series of calculations. These sophisticated calculations indicate that the design effectively limits transport of fluids within the shafts, thereby limiting transport of waste material to regulatory boundaries.

Each shaft seal includes a column of compacted WIPP salt with 1.5 wt% water added to the natural material. Construction demonstrations have shown that mine-run salt can be dynamically compacted to a density equivalent to approximately 90% of the average density of intact WIPP salt. The remaining void space is removed through consolidation caused by creep closure. The salt column becomes less permeable as density increases. The location of the compacted salt column near the bottom of the shaft assures the fastest achievable consolidation of the compacted salt column after closure of the repository. Analyses indicate that the salt column becomes an effective long-term barrier in fewer than 100 years.

The unique application of crushed salt as a seal component required development of a constitutive model for salt reconsoli-

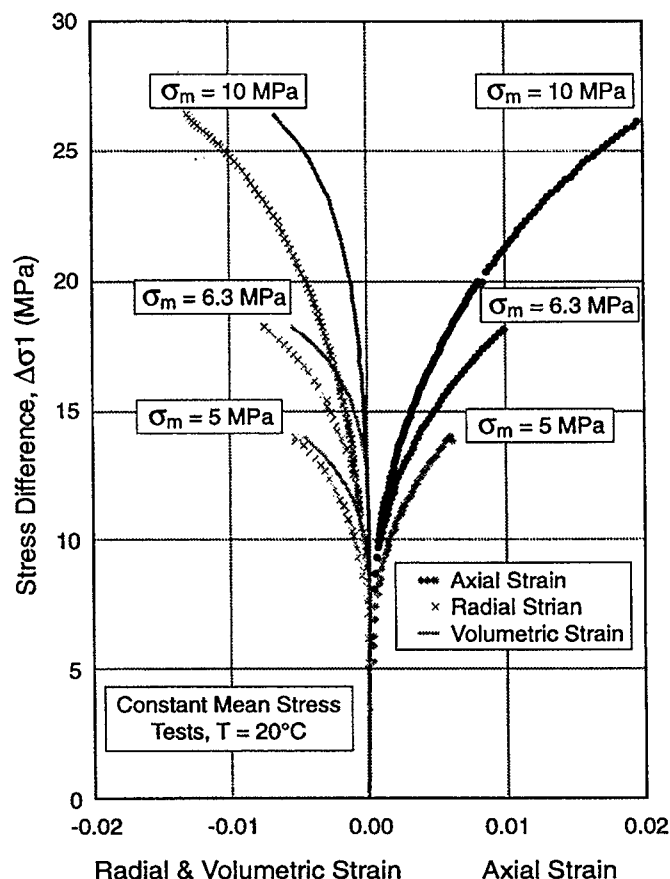


Fig. 5. Plot of strain as a function of constant mean stress.

dation. The model developed includes a nonlinear elastic component and a creep consolidation component. The nonlinear elastic modulus is density-dependent, based on laboratory test data performed on WIPP crushed salt. Crushed salt consolidation behavior combines the mechanisms of grain boundary pressure solution and dislocation processes. The constitutive model is generalized to represent behavior under three-dimensional states of stress. Upon complete consolidation, the crushed-salt model reproduces the creep model for intact salt (Eqs. 1-4). Parameters were obtained by fitting hydrostatic and shear consolidation test data gathered for WIPP crushed salt. Predictions were then validated against constant strain-rate data, which were not used for parameter determination. The resulting model for consolidating crushed salt is used to predict permeability of the salt column in the shafts.

A major function of many of the shaft seal elements is to prevent fluid transport to the consolidating salt column to ensure that pore pressure does not unacceptably inhibit the reconsolidation process. The relationship between salt column consolidation and seal component permeability derives from laboratory experiments on crushed salt. Results of these experiments are presented in Fig. 7. The seal design specifies an initial emplacement density of 0.90, or 90% of the intact density. Data collected at

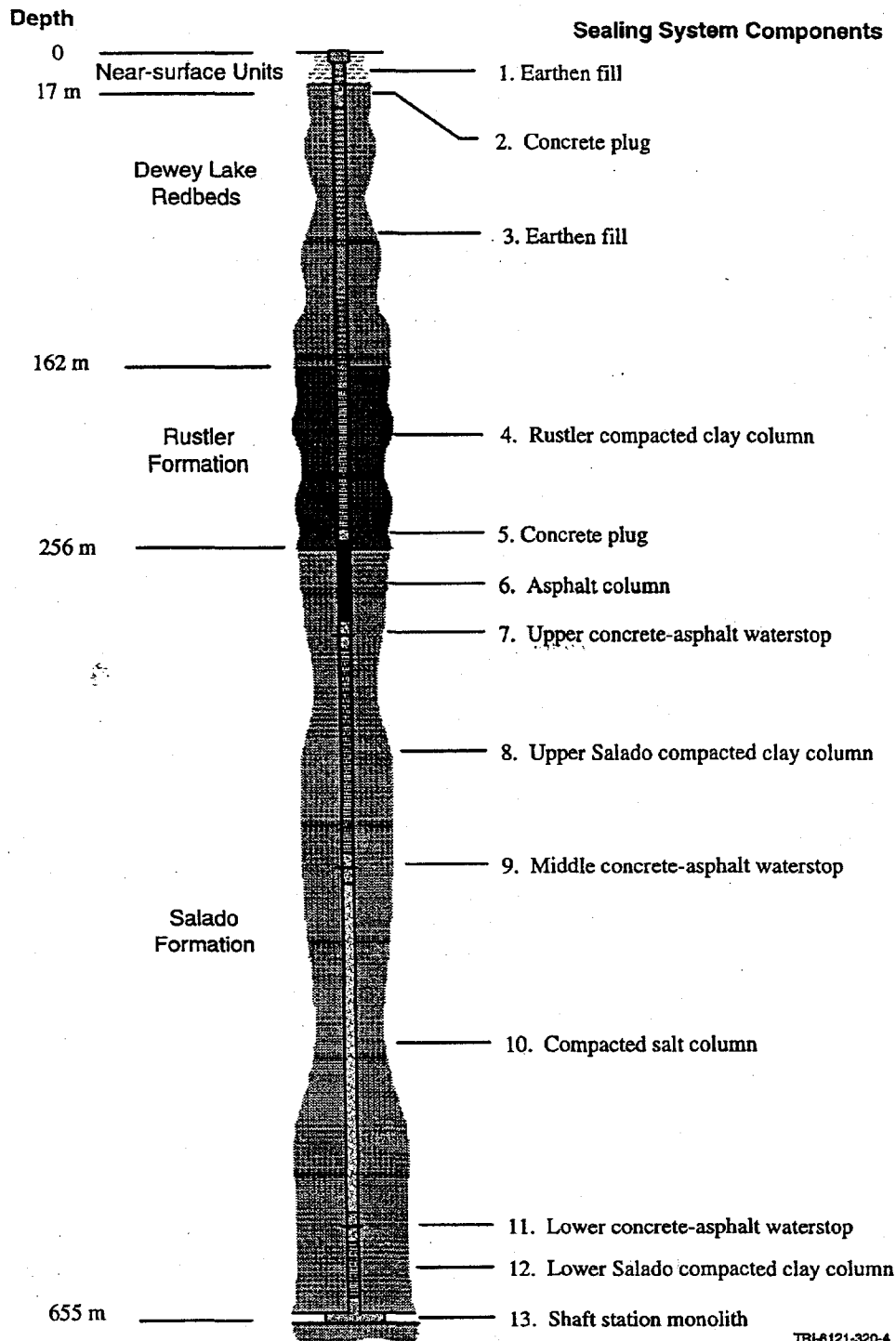


Fig. 6. Arrangement of the air intake shaft sealing system.

higher densities reflect the permeability of specimens upon reconsolidation in the laboratory. It is expected that consolidation processes will reduce connectivity of the pore spaces in the original salt column. The fractional density to permeability relationship implemented in the salt column model represents a range of the expected properties of the salt seal component. Calculations made to estimate fractional density of the crushed salt seal as a function of time, depth, and pore pressure show that consolidation time increases as pore pressure increases, as expected. At a constant pore pressure of one atmosphere, compacted salt will increase from its initial fractional density of 90%

to 96% within 40, 80, and 120 years after placement at the bottom, middle, and top of the salt component, respectively. At a fractional density of 96%, the permeability of reconsolidating salt is 10^{-18} m^2 , or lower.

Recent field tests, construction demonstrations, and laboratory test results have been added to the broad and credible database used to support predictive model capability. Results from a series of multiple-year, in situ, small-scale seal performance tests show that bentonite and concrete seals maintain very low permeabilities and show no deleterious effects in the WIPP environment. A large-scale dynamic compaction demonstration

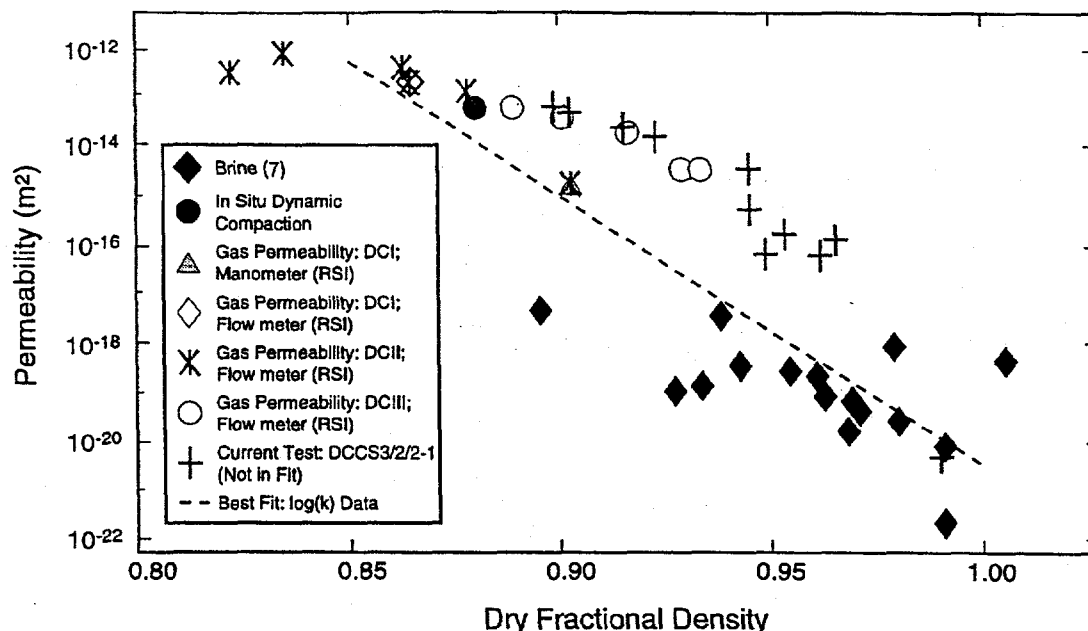


Fig. 7. Laboratory data of crushed salt permeability as a function of intact salt fractional density (6).

established that crushed salt can be effectively and densely compacted. Laboratory tests show that compacted crushed salt consolidates through creep closure of the shaft from initial conditions achieved by dynamic compaction to a dense salt mass with regions where permeability approaches that of *in situ* salt. These technological advances have allowed credible analysis of the shaft sealing system. Structural and hydrological analyses of those issues pertinent to seal system performance support the viability of the design.

An effective shaft seal system has been designed for the WIPP repository. Design guidance is addressed by limiting any transport of fluids within the shaft, thereby limiting transport of waste material to regulatory boundaries. The application or adaptation of existing technologies for placement of seal components, combined with the use of available, common materials, provide confidence that the design can be constructed. The structural setting for seal elements is compressive, with shear stresses well below the strength of seal materials. Because of the favorable hydrologic regime coupled with the low intrinsic permeability of seal materials, long-term stability of the shaft seal system is expected. Credibility of 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 ensure the desired sealing effect. The proposed WIPP shaft seal system adequately meets design and regulatory requirements and can be constructed with readily available materials and methods.

CONCLUDING REMARKS

Rock salt media provide excellent environments for permanent containment and isolation of hazardous materials, including radioactive waste. The WIPP Compliance Certification Application, approved by the EPA, combines thorough documentation of site geology, hydrology, and rock mechanics. As will be the case for any nuclear waste repository, rock mechanics and associated sciences play an overriding role in determination of site adequacy. Salt mechanics, believed to be more tractable

than brittle rock behavior, provides predictable assurance of long term performance. Robustness of waste repositories sited rock in salt is assured because of the ideal characteristics of the medium to encapsulate, contain, and isolate the emplaced waste.

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