From science to compliance: Geomechanics studies of the Waste Isolation Pilot Plant

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ABSTRACT: Mechanical and hydrological properties of salt provide excellent bases for geological isolation of hazardous materials. Regulatory certification of the Waste Isolation Pilot Plant (WIPP) testifies to the nearly ideal characteristics of bedded salt deposits in southeast New Mexico. The WIPP history includes decades of testing and scientific investigations, which have resulted in a comprehensive understanding of salt's mechanical deformational and hydrological properties over an applicable range of stresses and temperatures. Comprehensive evaluation of salt's favorable characteristics helped demonstrate regulatory compliance and ensure isolation of radioactive waste placed in a salt geological setting.

1. INTRODUCTION

Mechanical and hydrological properties of salt provide excellent bases for geological isolation of hazardous materials. Regulatory certification of the Waste Isolation Pilot Plant (WIPP) stands as testament to the widely held conclusion that salt formations provide excellent isolation media. The WIPP saga began in the 1950s when the US National Academy of Sciences (NAS) recommended a salt vault as a promising solution to the national and international problem of nuclear waste disposal. Sandia National Laboratories (SNL) has served as the science advisor for the WIPP project for over twenty years. The scientific basis for the NAS recommendation has been fortified through a series of large-scale in situ field tests and laboratory investigations, which underpin rock mechanics analysis and performance assessment modeling. These scientific investigations helped develop a comprehensive understanding of salt's deformational behavior over an applicable range of stresses, temperatures, and time. Constitutive modeling, validated through underground testing, provides the computational ability to model long-term behavior. In concert with advancement of the mechanical models, fluid flow measurements show the evaporite lithology to be essentially impermeable and the WIPP setting to be hydrologically inactive. These studies paved the road—from science to compliance—for the WIPP.

The WIPP facility, as certified by the US Environmental Protection Agency, received its first shipment of transuranic waste on March 26, 1999. This historic moment culminated decades of dedicated research and development. The concept of isolating hazardous materials from the biosphere by deep geological storage now enjoys wide support in the scientific community. The WIPP Compliance Certification Application combined a thorough documentation of site geology, hydrology and rock mechanics.

The WIPP is a geological disposal operation for permanent isolation of transuranic defense waste in the United States. Its location in salt provides an ideal setting for such a disposal site and makes a discussion of its recent history particularly germane to this conference. The WIPP program began embryotically in 1957, when the NAS recommended salt disposal as a suitable for closing the nuclear cycle. The site in southeastern New Mexico was identified as a candidate in the early 1970s after a similar site in Kansas was rejected. Although salt provides a sound medium for disposal from a technical perspective, much of the ultimate success in siting the WIPP has as much to do with political wherewithal as with its favorable technical attributes. As shown in Figure 1, many milestones in the history of WIPP are political decisions and documents, rather than scientific breakthroughs.

Nonetheless, the regulator for certifying the WIPP, the US Environmental Protection Agency (EPA), required a rigorous performance evaluation of the site during the licensing process. This paper reviews highlights of the geomechanical programs, which lent strong support to the compliance demonstration.

Milestones for Disposal of Radioactive Waste in the US	
1943	Atomic Energy Commission's (AEC's) earliest decision on managing waste: Store high level waste (HLW) as liquids in tanks and bury other waste (solid or liquid) in trenches.
1944	Disposal of nuclear waste begins on site at Los Alamos National Laboratory (LANL).
1952	Idaho National Engineering Laboratory (INEL) completes Radioactive Waste Management Complex (RWMC).
1953	Savannah River Plant (SRP) begins waste storage and disposal on site at "Old Burial Ground."
1954	Rocky Flats Plant near Denver, CO begins shipping transuranic waste to INEL for disposal at RWMC.
1957	NAS recommends radioisotope waste disposal in salt as most promising method. Oak Ridge National Laboratory (ORNL) begins research in salt (1957-61)
1961	NAS reaffirms use of New Mexico salt beds for disposal. Gnome nuclear detonation test near Carlsbad, NM as part of Plowshare Program.
1963	ORNL begins Project Salt Vault.
1970	Conceptual design completed for HLW repository in salt.
1971	Congress directs AEC to stop project at Lyons, KS until safety is certified.
1976	Project is officially named the Waste Isolation Pilot Plant (WIPP). SNL begins site characterization and engineering design program at new site.
1979	Congress passes WIPP bill.
1981	First WIPP shaft drilled. DOE publishes Record of Decision to proceed with Site Preliminary Design Validation phase.
1982	Second shaft completed.
1983	Full construction begins.
1984	SNL begins fielding many underground experiments.
1985	EPA promulgates 40 CFR 191.
1988	WIPP begins drilling fourth shaft after reevaluating 1981 decision to eliminate it. SNL reports on *in situ* permeability (1000 times lower than 1979) and small potential brine inflow.
1990	Construction officially complete.
1992	WIPP Land Withdrawal Act (LWA).
1993	EPA announces intent to promulgate 40 CFR 194 to specify requirements for implementing 40 CFR 191 at WIPP.
1996	EPA promulgates 40 CFR 194. DOE sends 400-lb Compliance Certification Application (CCA) to EPA. DOE issues 84,000-page second supplemental draft (Environmental Impact Statement).
1999	First shipment of waste.

Figure 1. Timeline of WIPP highlights.

2. LARGE SCALE FIELD 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 storage panels (as shown in Figure 2). 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 [1]. Primary *in situ* experiments involving rock mechanics included (1) Thermal/Structural Interactions, (2) Defense High Level Waste Mockup, (3) Defense High Level Waste Overtest, (4) Heated Axisymmetric Pillar, (5) Plugging and Sealing Tests, and (6) Waste Package Performance Tests.

Many smaller scale underground investigations, such as those pertaining to hydrology and seal materials, were undertaken. Some of these are noted in the legend on Figure 2. *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

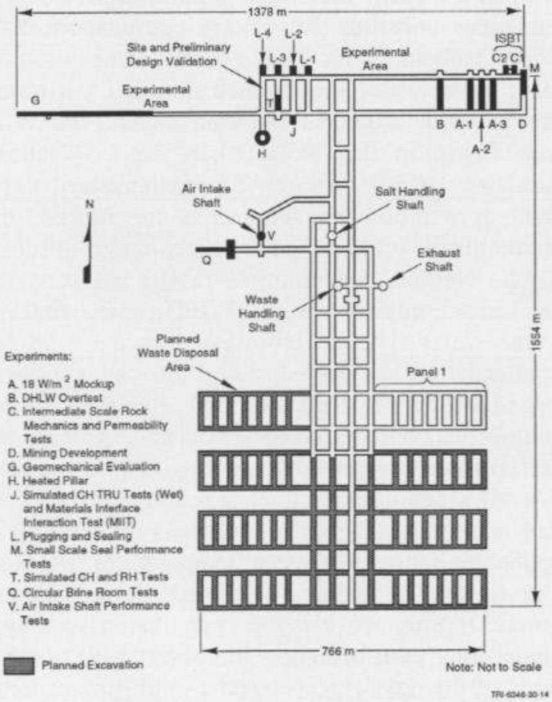

Figure 2. Plan View of WIPP Showing Experimental Area and Projected Storage Area.

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 experiments. Thermal/Structural Interaction tests simulated defense high level waste disposal, 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. Agreement was high between underground test results and predicted closure rates. Ambient closure in unsupported WIPP storage rooms reached 25% in the ten years after excavation. Based on a tremendous amount of *in situ* data, an acceptable creep model was validated, effectively replicating observed behavior [2]. The model itself, consistent with *in situ* experiments, has been generalized to facilitate comparison between 2-D and 3-D calculations. This suite of geomechanical underground experiments helped build a solid understanding of the structural response of a repository situated 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" [3].

3. LABORATORY TESTING

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. Concurrent with siting of the WIPP, the United States 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 European 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.

Thermally activated deformational mechanisms are represented by exponential expressions in the constitutive model. Optical and scanning electron microscopy have confirmed microprocesses operating over temperature and stress regimes relevant to nuclear waste repositories, as documented in the optical photomicrographs in Figure 3. Generally, small strains initiate dislocation multiplication (3a). Glide along dodecahedral planes is readily activated. Small thermal activation allows cross slip of glide dislocations (3b), whereas higher temperatures (e.g., 100°C) provide sufficient thermal activation to promote recovery processes, illustrated by polygonized substructures (3c). 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 salt is suppressed. The initiation of dilatancy and a functional relationship between volumetric strain and permeability are being investigated in current laboratory programs.

Thus, laboratory geomechanical research provides both basic and applied technical bases supporting WIPP's compliance application.

4. SHAFT SEAL SYSTEM DESIGN

Most geologically based repositories would provide ingress, egress, and ventilation through shafts, which provide direct linkage to the biosphere.

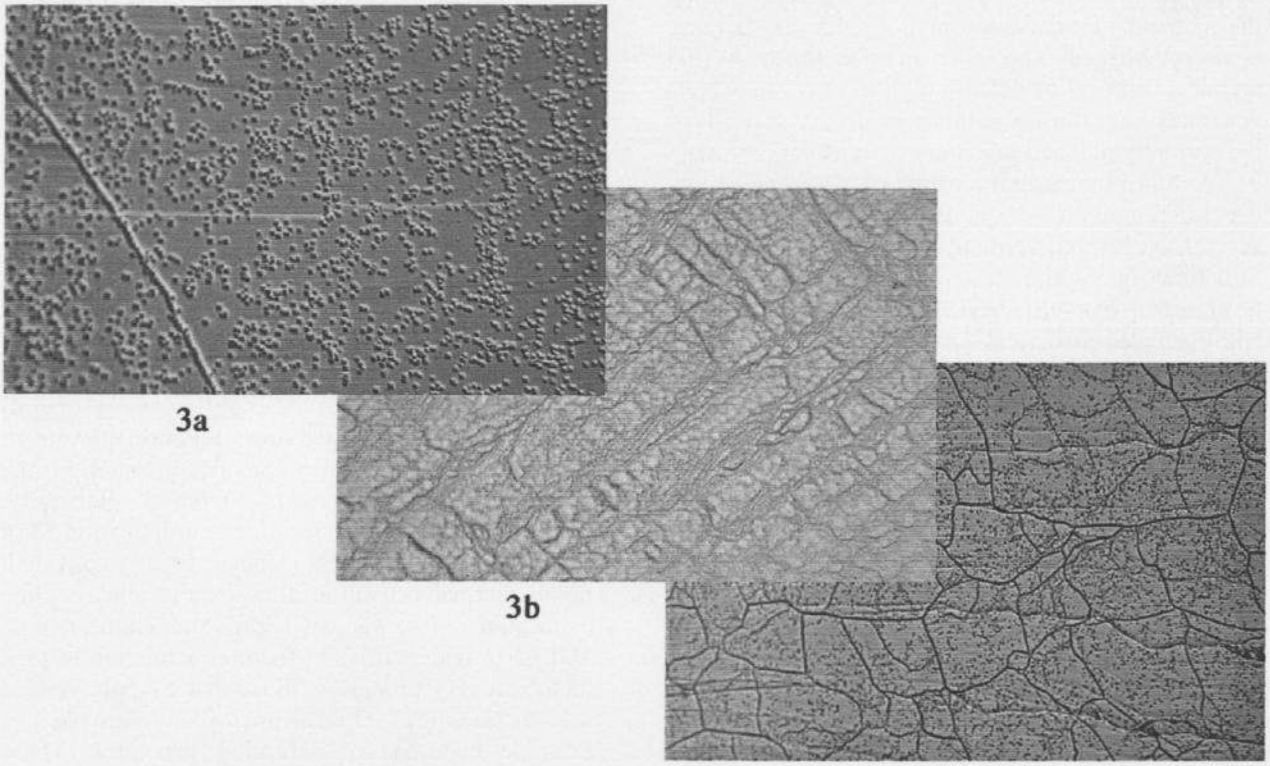

Figure 3. Microscopy of deformed salt structures showing free dislocation density, glide with cross slip, and polygonization.

Decommissioning and abandonment surety depends on the ability to provide an engineered barrier within the shafts. 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. 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 design described here 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 Figure 4, the shaft seal system comprises thirteen 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 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.

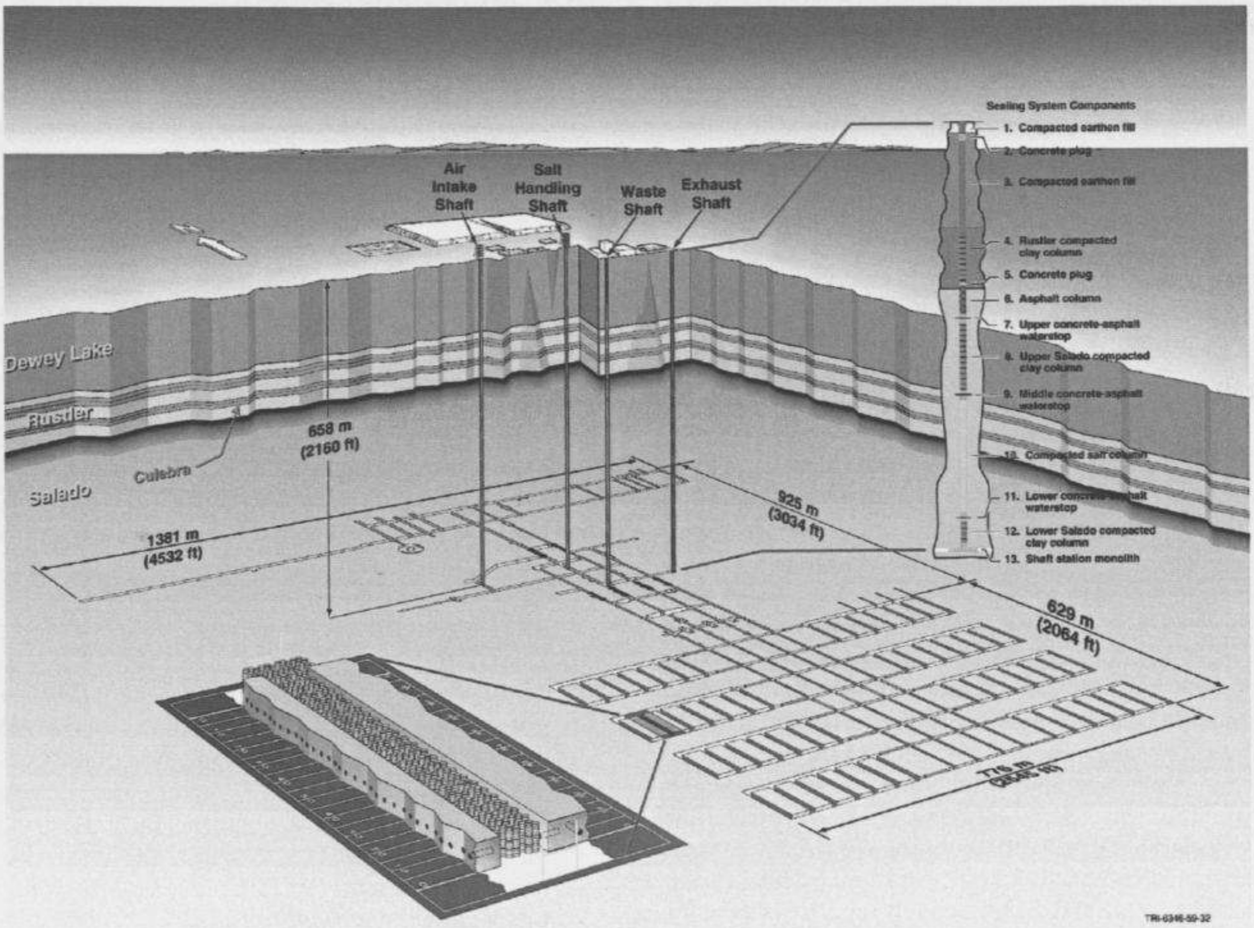

Figure 4. Isometric view of the WIPP, showing shaft sealing components.

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 [4].

Unique application of crushed salt as a seal component required development of a constitutive model for salt reconsolidation. 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. At complete consolidation, the crushed-salt model reproduces the creep model for intact salt. Parameters are obtained by fitting hydrostatic and shear consolidation test data gathered for WIPP crushed salt. Predictions are then validated against constant strain-rate data, which were not used for parameter determination. The model for consolidating crushed salt is used to predict permeability of the salt column.

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. The seal design specifies an initial emplacement density of 0.90, or 90% of the intact density. Data collected at higher densities reflect the permeability of specimens after 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. 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 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 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 and have contributed significantly to compliance certification.

5. CONCLUDING REMARKS

In October 1996 the DOE submitted the Compliance Certification Application (CCA) to the EPA. The CCA represented more than twenty years of scientific studies, including geomechanics. Independent technical peer review allowed the regulator to determine that WIPP scientific and engineering studies were sufficient to assure regulatory compliance.

Salt media appear to be ideal sites for waste disposal. Usually, salt occupies massive lateral and vertical extent, is aseismic and impermeable. Adequate bases for disposal operations have been demonstrated for radioactive waste isolation in the United States. Building on the WIPP experiences and its scientific, engineering, and regulatory justification, it would seem to suggest that salt media might be explored for other disposal functions in the United States and other countries.

6. REFERENCES

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