

Salt Rock Mechanics—Prediction vs. Performance--WIPP Provides Answers- **10411**

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ABSTRACT

Salt formations hold great promise for disposal of vast quantities of nuclear wastes. The concept of permanent disposition in salt is not new, but perhaps a renewed impetus for exploring salt disposal is upon us once again. Since the 1950s, salt formations in the United States have been recognized as possessing favorable disposal attributes because they are widely available at sufficient depth and areal extent, exhibit low permeability, are easy to mine, and possess advantageous thermal properties. Experience with the Waste Isolation Pilot Plant demonstrates that the predicted, ambient evolution of the underground has been confirmed through performance. The basic research on salt mechanics in the past included thermomechanical studies and some thermally driven salt properties could improve closure and encapsulation potential for salt disposal. This paper, reviews the state of salt mechanics knowledge, including our nation's considerable laboratory research, field testing, constitutive model development and micromechanical understanding. Radioactive waste isolation in salt has been a long-held concept for closing the nuclear fuel cycle. Today, in view of more than ten years of successful operation of WIPP, the promise of salt as an isolation medium is greater than ever.

INTRODUCTION

In the years leading up to the Compliance Certification Application in 1996, scientists working on the Waste Isolation Pilot Plant (WIPP) repository project conducted an extensive suite of laboratory and field experiments. Full-scale experiments in the underground established performance standards and expectations, while the fundamental science of salt deformation was explored in the laboratory. Field experiments included several at elevated temperature to ascertain salt response under conditions anticipated for the operating repository, which at the outset included heat-generating defense waste. Simulations and predictions of the field tests were made using finite element computer models that incorporated sophisticated models for salt deformation. Parameters for the salt model were derived from laboratory experiments on natural salt extracted from the repository horizon. All of these science investigations provided confidence in the predicted behavior of the salt at WIPP. After more than a decade of WIPP operations, this paper recounts some of the geomechanics investigations conducted during site characterization, highlights three key geomechanics issues experienced thus far, and concludes that our basic understanding of salt mechanics portends a promising future for radioactive waste disposal in salt.

THE BEGINNING

The geologic repository community has long-considered salt as a viable medium for disposal of hazardous materials, including nuclear waste. A well known study [1] undertaken by the United States National Academy of Sciences in the 1950's stated:

“The most promising method of disposal of high level waste at the present time seems to be in salt deposits. The great advantage here is that no water can pass through the salt. Fractures are self sealing...”

Over time a considerable body of research has been conducted to advance the state of knowledge with respect to isolation of waste in salt. Field and laboratory studies were pursued in Germany and the USA, which provided the background understanding of salt mechanical, hydrological, and thermomechanical response to anticipated repository conditions. Laboratory and field investigations further established fundamental attributes of salt as a geologic isolation medium, such as salt's ease of mining, wide geologic distribution and geologic stability, relatively high thermal conductivity, and impermeability.

The initial concepts for disposal in salt and the eventual identification and viability of the salt deposits near Carlsbad NM coincided with development of national nuclear waste policy. In the 1960s, Oak Ridge National Laboratories conducted a large-scale field test called Project Salt Vault in the bedded salt formations near Lyons Kansas [2]. The potential site near Lyons was eventually abandoned in the early 1970s and shortly thereafter the salt in the Delaware Basin near Carlsbad NM was brought forward as a possible site. This transition of potential repository sites was accompanied by a change in the lead national laboratory from Oak Ridge to Sandia National Laboratories. As the national policies were being sorted out, significant research programs were undertaken to evaluate suitability of salt for nuclear waste disposal. After ten years of operations and more than 8000 shipments, we take a look back at some of the early research into salt characterization before operations began. The well established scientific bases provided the tools necessary to address geomechanics issues encountered during the first decade of operations. The WIPP success, built on a broad understanding of salt behavior, bodes well for future nuclear waste disposal solutions in salt.

SITE CHARACTERIZATION AND LABORATORY STUDIES

Despite the fact that civilization had been mining salt for millennia, at the beginning of the WIPP investigations there was little directly applicable experience in thermomechanical salt response, as needed for repository design, analysis, and operations. Considerations of the long-term behavior required detailed understanding of deformational processes, such that extrapolations could be made beyond human experience. Research involved with the microstructural processes were pursued in the laboratory, while full-scale demonstrations were deployed in the underground. Design specifications for operations needed such fundamental information as how long a disposal room would stand up as well as how the natural bedded salt would respond to thermal loads. The research activities undertaken in the pilot plant stage investigated processes from the atomistic level to the full scale, a range of some ten orders of magnitude.

Initial site characterization for WIPP included both field and laboratory studies. The laboratory work necessitated development of prototype testing machines because of the large grain size of natural rock salt and representative repository test conditions, such as constant stresses and temperatures for long periods of time. To answer the need, a suite of special testing machines as shown in Figure 1 were built.



Fig. 1. Salt testing machines (courtesy RESPEC)

The first laboratory tests were conducted on salt and anhydrite from WIPP site characterization drill holes. After the underground was accessed, much more core became available from the selected horizon. Tests were conducted over confining pressures to 15 MPa (approximately the lithostatic stress at the WIPP horizon) and temperatures to 200°C. Under most conditions involving elevated temperature and modest confining pressure, salt deforms plastically. This phenomenon of flow without fracture is one of the primary features of salt as a disposal medium.

The laboratory experiments documented the macroscopic deformation as a function of time, temperature and stress. Hundreds of months of testing produced creep data for the constitutive models. Figure 2 contains photographs of typical deformed salt samples and examples of their substructures. Deformation was induced by stresses and temperatures, and accomplished by crystal-plastic processes. Etched cleavage chips at high magnification on an optical microscope highlighted the salt substructures. Laboratory tests and microscopy established the physical processes of salt deformation and quantified model parameters for repository relevant conditions.

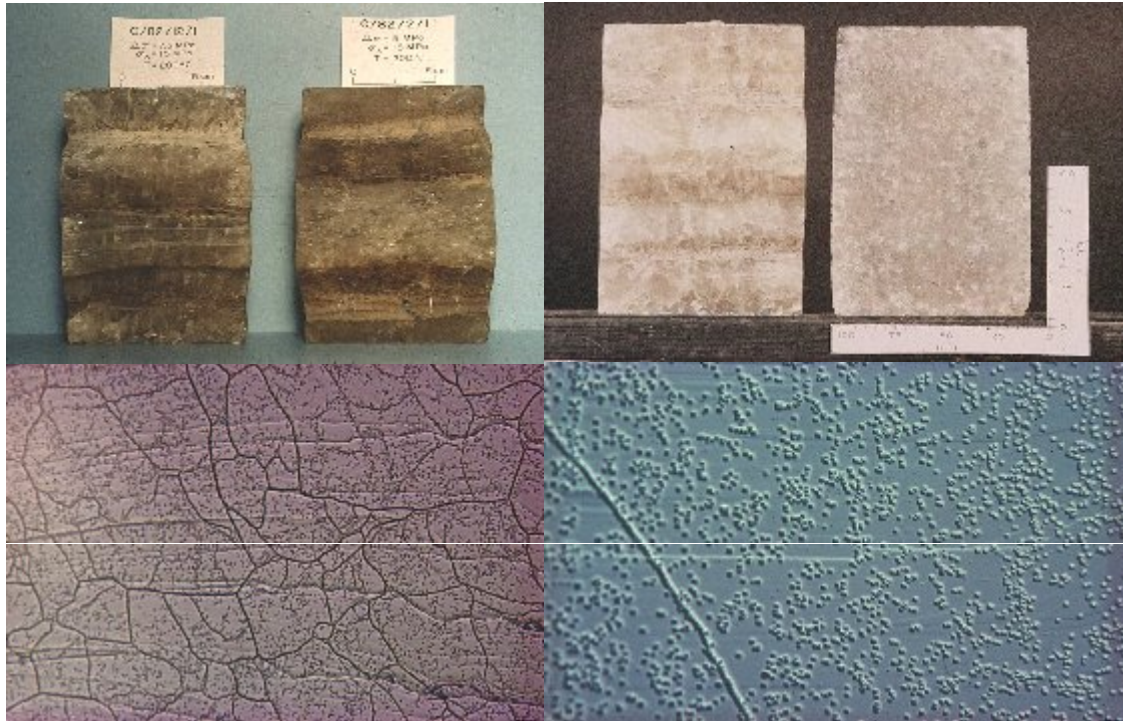


Fig. 2. Deformed salt samples and their microstructure.

It is possible for salt to fracture under certain conditions, but these fractures self heal at low confining stress. Salt deformation is accompanied by significant fracturing at room temperature in an unconfined state, conditions that occur near free surfaces of the repository openings. Salt therefore exhibits brittle deformational processes near the roof, floor and walls, but deforms by constant volume processes at depth within the rock formation. Studies showed that stress conditions that promote fracture and those that promote crystal plasticity were clearly defined. Conditions of the brittle-to-ductile transition have been widely study by WIPP scientists [3] and research colleagues in Germany [4]. By plotting the data using stress invariants, a simple criterion was developed to model fracture in the WIPP underground. Applying the model, WIPP scientists are able to calculate the evolution of the disturbed rock zone (DRZ) for salt around repository openings.

Field tests in the underground test facility provided proof-of-principle for operations as well as large-scale thermomechanical response. Figure 3 shows the WIPP layout pertaining to the experimental and disposal program in the 1980s, including both the testing area in the north region of the facility and the future disposal panels in the south region.

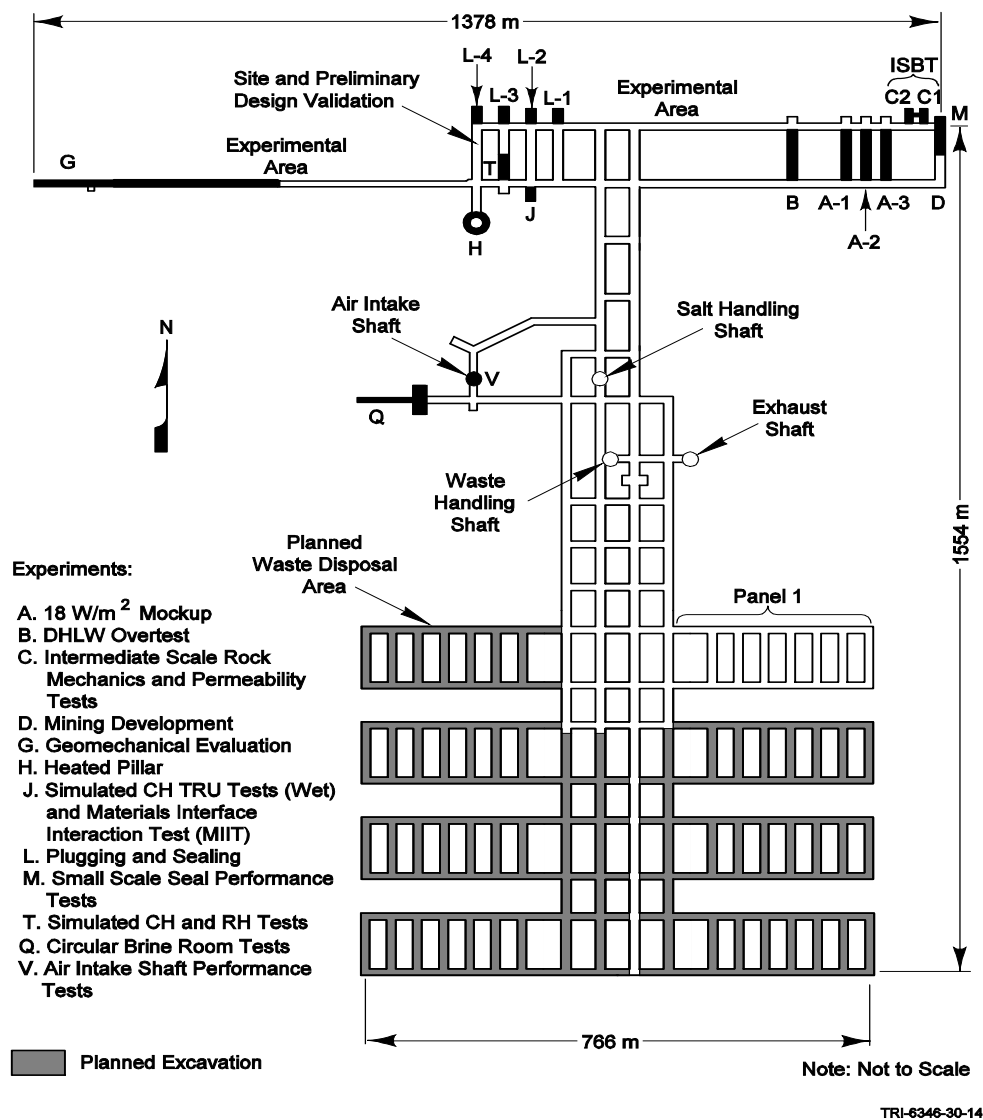


Fig. 3. Layout of WIPP experiments and disposal area in the 1980s.

A large number of experiments validated preliminary design expectations, demonstrated key operational concerns, and quantified thermomechanical responses. Figure 4 is a photograph of one of these typical experiments and shows a mock up of high-level waste placed in a room generating a thermal load of 18 W/m². Field demonstrations such as this one provided confidence that disposal operations could be conducted, while laboratory studies provided the scientific understanding of salt properties.



Fig. 4. One of the several thermomechanical tests at WIPP.

OPERATIONS FOR THE FIRST TEN YEARS

The full-scale site characterization demonstrations, laboratory experiments and models provided the understanding necessary to certify/license and operate the facility. The basis for the eventual Compliance Certification Application was changed appreciably by nuclear waste policy, especially the Nuclear Waste Policy Act amendment in 1987, when Congress decided to characterize only the Yucca Mountain site in Nevada as a commercial spent-fuel and high-level waste repository. The inventory to be placed in WIPP no longer included materials that generated heat, so the large-scale thermal tests in the WIPP underground were discontinued. However, much of the experimental program was conducted under ambient conditions and provided the basis for the Compliance Certification Application. Ten years of operations at WIPP have provided opportunities to evaluate the adequacy of the science upon which the regulatory compliance certification was based.

A baseline concept of operations was compiled and a successful compliance certification was obtained. Subsequently, changes to the original concepts were necessary for a variety of reasons. These included a requirement for a robust panel closure system, its effect on salt fracturing behavior, and an operational decision to raise the disposal elevation. Ongoing certification by the Environmental Protection Agency necessitated that deviations from the analyzed baseline be evaluated for impact to the long-term performance assessment.

PANEL CLOSURE SYSTEM

The first certification of compliance issued by the EPA included selection of a panel closure system from four design options (A, B, C, and D) as a condition of certification. The selection--

Option D--includes a 3.7 m concrete block wall and a 7.9 m concrete monolith. If and when the concrete monolith is constructed, its presence will change the characteristics of the neighboring salt. Modeling detail was added to the performance assessment to incorporate a more realistic representation of the geotechnical behavior near the concrete monolith element, including permeability values and geometrical extent of the disturbed zone.

A rigid plug--such as the Option D panel closure concrete--would create stress conditions conducive to fracture healing. Thus, the expectation is that any fractures around the area where the concrete monolith is placed would be healed as the creeping salt compressed against the concrete. Fractures around existing openings constitute one physical feature that defines the damage zone enveloping disposal rooms. The Option D panel closure system also affects the mechanical and hydrological properties of other rock layers sandwiched in the salt. The original repository horizon is closely underlain by an anhydrite marker bed (Marker Bed 139), nominally 1 m thick. The presence of non-salt materials and their distance from the openings have important performance implications. For example, anhydrite fractures would not be expected to heal in the same manner as salt.

The block wall element of the Option D panel closure system is a highly conservative barrier that was designed to protect against explosion of gases created by waste degradation. When the explosion walls were constructed in the entries of the first and second panels no further monitoring within the panel was possible. Rather than constructing the block wall for the third panel, a progressive monitoring approach was adopted. After Panel 3 was filled with waste, gas sampling and geotechnical measurements were continued in Panel 3. No explosive gas has been collected thus far and extended room closure measurements substantiated the predicted closure rates.

DISTURBED ROCK ZONE

Salt's plastic deformation is a positive quality for waste isolation. Room closure is largely a result of plastic (constant volume) deformation of salt into the open space. However, near the walls, roof and floor of each room the stress conditions are such that fractures in the salt can be created. As salt creeps into the room it eventually contacts the waste stacks and begins to compress the repository contents. In fewer than 100 years the state of stress in the salt around the waste rooms will approach the original condition of no shear and the salt fractures around the waste rooms would be largely healed as well. If the waste form generated heat, salt creep deformation would be accelerated.

Field and laboratory evidence provides confidence that the damage created in salt will heal rapidly as the stress differences diminish. The creation and subsequent healing of salt fractures around a disposal room or a closure system element are important for both operations and long-term safety analyses. The properties that typically define the DRZ [5] include: (1) fractures from microscopic to readily visible scales, (2) loss of strength evidenced by rib spall, floor heave, roof degradation and collapse, and (3) increased fluid permeability via connected porosity. The WIPP program has continued to make observations and measurements to further understand the response of salt, including damage reversibility. Development of fractures near the opening

begins rapidly and slows over time. Several complementary methods, such as sonic velocity and optical microscopy, have been applied to measure the disturbed zone.

RAISED DISPOSAL HORIZON

The repository horizon was raised to improve ground control. Panels in the northern part of the disposal area remain at the original horizon, whereas panels further south are elevated 2.43 m. The roof of the raised waste rooms is mined to coincide with a stratigraphically discernable clay seam. The prevailing room condition at the original horizon involves a manifestation of fractures, which arch over the room and asymptotically connect to a thin clay seam. Predictions of room closure are fundamental to safe operations and to performance assessment calculations that support the compliance basis. Calculations dating back many years predicted room closure rates that would bring the salt in contact with the magnesium oxide sack on top of the waste stack in about 20 years. Now that measurements within Panel 3 have been extended, geotechnical data are being collected that validate the predicted closure rates. Geomechanical effects of raising the repository horizon were calculated, but because the stratigraphy surrounding the disposal room averages 95% salt (NaCl), there was essentially no room closure difference between the raised and the original horizon.

Raising the disposal horizon increased the distance from the repository floor downward to Marker Bed 139 from 1.4 m to approximately 3.8 m. Based on calculations, this change was sufficient to suppress salt damage below the anhydrite marker bed, whereas the salt disturbed zone developed below the marker bed at the original horizon.

THE FUTURE

The WIPP site was well characterized and understood before disposal operations began. More years of disposal experience has demonstrated that the time-wise deformation and fracturing characteristics have reliable predictive models. Changes to the compliance baseline, particularly the regulatory requirement to implement a robust panel closure system, represent significant departures from the analyses run for the original compliance performance assessment and the verification test that followed. The DRZ model was updated to depict more accurate geometries and properties of the DRZ than portrayed in the original certification. The operational enhancement of elevating the disposal horizon was evaluated in terms of room closure and the resulting porosity, which in turn is sampled in performance assessment. Details involved with elevating the disposal horizon also provided insight to the local behavior of the DRZ evolution and devolution and the distortion of the anhydrite layers near the disposal rooms. This information supported the analytical treatment of the panel closure.

Throughout the ten years of operations, descriptions and documentation of salt damage properties and technical updates have advanced the body of knowledge pertaining to the DRZ. Calculations showed that prediction of the forward evolution of the DRZ replicates observations in the WIPP underground. The size and shape of the DRZ around an opening based on a stress invariant criterion are similar to the size and shape derived from sonic velocity studies and microscopy. Total encapsulation expected under ambient conditions, would be accelerated with temperature. Salt damage healing and the eventual entombment of the waste remain attractive features favoring disposal of radioactive waste in salt.

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