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Capturing Early Evolution of Salt Openings

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ABSTRACT: In situ tests implemented in a research facility mined from salt deposits, if planned appropriately, provide an opportunity to characterize the host rock before, during, and after excavation of test rooms. Characterization of the test bed is essential to interpret structural deformation, creation and evolution of the disturbed rock zone, and measurement of first-order hydromechanical properties as the salt evolves from an impermeable undisturbed state to a more-transmissive damaged state. The strategy expounded upon in this paper describes recommended geophysical measurements to characterize the initial state of a potential test bed and its evolution over the course of a field test. Discussion includes what measurements could be made, why the measurements would be made, how they are made, and how accurately they need to be made. Quantifiable parameters will establish field-scale boundary conditions and data quality objectives to characterize the test bed in an underground salt research facility.

1. INTRODUCTION

Salt formations enjoy many favorable characteristics that combine to make them promising media for permanent radioactive waste disposal [1]. Salt formations are plentiful in the United States, providing ample areal extent and substantial thickness in aseismic geologic settings [2]. In addition to high thermal conductivity and plastic deformational response, undisturbed salt has extremely low permeability and porosity. Some of the favorable characteristics are modified during the excavation process and evolve during operations. Accounting for these fundamental structural and hydrologic changes is essential for establishing credible repository performance models needed to support waste disposal licensing activities. Before conducting experiments or operational demonstrations in a salt underground research facility, significant changes have already occurred in the salt, leading to a disturbed environment for hosting experiments. The disturbed rock zone (DRZ) near the excavation free surfaces contains inter-connected flow paths between pre-existing, but previously impermeable formation brine filled porosity, and becomes an anisotropic region of higher permeability and porosity. Depending upon experiment objectives, liberated brine, either in the vapor or liquid phase, and increased porosity can significantly influence evolution of the test bed. In addition, transient creep strain accumulates rapidly at the onset of excavation, but is not measurable once mining has already occurred. Using only observations from within the excavation overlooks potentially large strain accumulation in the salt formation. To model salt deformation completely, we must account for the transient creep contribution. Fortunately, evolutionary characteristics of salt are qualitatively known and straightforward engineering measurements can be made to quantify early evolution. This can allow the experimentalist to capture fully the early deformation for structural model development and validation.

Investigations that utilize a mined salt formation for experimental activities would benefit greatly from the knowledge of 1) initial, undisturbed conditions, 2) the evolutionary changes imparted by excavation, and 3) the boundary conditions and system state extant when field activities are undertaken. These same investigations are equally important for designing and predicting excavation sealing structures. Here we describe the essence of a Test Plan to quantify conditions before space is opened and to measure the evolution of displacement, strain, damage, and permeability that occurs during and after excavation. Testing of this nature would support virtually any type of field demonstration or test that involves room-scale excavation in a geologic salt formation.

Our concept looks forward in time and considers possible testing or demonstration activities to be performed in a yet-to-be excavated space. The particular size, length and geometry of the excavation are assumed for purposes of discussing this test strategy. The described host-rock characterization program begins from a minimally disturbed state where instrumentation is installed at the periphery of test rooms *before* room mining begins. As mining progresses, changes are measured as stresses are redistributed, the rock deforms and damage processes ensue.

The primary approach for functionally characterizing the DRZ is by use of fluid-flow test boreholes, injecting gas or brine into borehole intervals in the areas where hydro-mechanical changes are expected to occur. This testing program will make deformation and fluid flow measurements at similar locations so that unambiguous correlations can be established between rock deformation and permeability changes. The arrangement of instrumentation and measurement techniques allows establishment of initial (undisturbed or minimally disturbed) conditions, capture of the rapid transient response during initial excavation, and continuous monitoring the salt as it creeps toward the newly created excavation. Measurement of mechanical response coupled with hydrologic changes establishes boundary conditions for tests or demonstrations conducted later in the excavation.

To demonstrate the monitoring concepts, a hypothetical test configuration is assumed. An existing tunnel (N 940) serves as an access opening for drilling and installing instrumentation into the virgin ground. A new excavation 16 feet wide and 10 feet high will be mined parallel to N 940 and separated by 35 ft. To introduce natural variability into this discussion, stratigraphy of the formation is assumed to be comparable to that encountered in the Permian Salt at the Waste Isolation Pilot Plant (WIPP). Evaluation of this stratigraphy provides insight to mechanical behavior of nearby non-halite strata in an otherwise halite formation. In addition, there is significant confidence in WIPP structural deformation predictive models, which have been validated against decades of in situ measurements.

An underground research facility in salt provides an opportunity to measure undisturbed permeability, which is expected to be almost immeasurably low. Beauheim and Roberts [3] summarize many permeability measurements in the near and far field and in interbed lithologies. Excavation perturbs the stress state and the static salt formation begins to deform into the opening. The process of mechanical deformation (dilation) creates micro- and macro-fractures surrounding and preferentially parallel to the openings. Fracture damage creates permeability and porosity that did not exist before mining and the accessible brine moves down stress and pressure gradients toward the opening. Initially, much of the brine flows into fill the newly created halo of porosity surrounding the excavation. Some brine reaches the walls of the opening and is evaporated and removed from the system by ventilation air. Some brine remains in the DRZ and flows by gravity into void space created under the floor by flexure. The brine below the floor may continue to flow down the geologic slope of a bedded salt formation, depending on the stratigraphy. The extant conditions in the drift before future testing begins are controlled by the creation of the DRZ, its geometry and hydro-mechanical properties, and the distribution of brine.

From this point, we describe activities in sufficient detail to enable an appropriately trained technical team to implement the test program. The general objective of these test activities is to characterize the mechanical and hydrologic boundary conditions associated with room excavations. The level of characterization should be sufficient to enable correct and accurate interpretations of how those boundary conditions influence phenomena inside the test room. The specific technical objectives are:

- Monitor rock mass deformation in the near-field around excavations to confirm behavior consistent with previous measurements within geologic salt formations. This includes installing extensometers before mining.
- Monitor evolution of fluid flow properties in the host rock around the room to characterize the effects mechanical damage has on the hydraulic properties of the rock mass. This effort includes installing

fluid flow test completions in the unmined rock mass before mining.

- Monitor ambient air pressure in the test rooms and the near-field rock from gas fluid-flow test holes. When creep damage is sufficient, barometric pressure within the mine will influence the ambient gas pressure measured in the near-field rock, which can allow air circulation and lead to drying of the room surfaces and the DRZ.

Early time mechanical and hydrologic response of the salt formation can be predicted by calculation, monitored for confirmation, thus validating the computational simulation.

2. SALT BEHAVIOR

To explain the testing strategy, some assumptions of the configuration are necessary, mindful that the philosophy, evolution, and measurement concepts are adaptable to various opening geometries. The surrounding stratigraphy is predominantly halite, though bedding layers of clay and anhydrite are common in halite formations and will be included in discussions here.

Mechanical deformation of the rock surrounding excavations controls the development of *initial* or *boundary* conditions for subsequent experimental work in the excavations. Geomechanical deformation comprises instantaneous elastic deformation concurrent with stress redistribution, transient creep, dislocation creep, and damage imparted to the host rock under certain stress conditions. Combined, these processes can be quantified in aggregate through observations of deformation rates, finite displacements, and characteristics of the DRZ.

2.1 Geomechanical Measurements

Proposed testing techniques have been used previously in salt applications and can be considered generic. The instruments would be arranged around a to-be-mined underground research laboratory drift configuration appropriate for geologic waste disposal. Testing and monitoring include primary measurements of deformation, strain rate, and brine and gas flow and secondary measurements of temperature and barometric pressure.

Salt creep has been extensively measured and characterized by U.S. and German salt repository programs, solution cavern industry, and salt and potash mining. Crystal plasticity is isochoric—meaning it does not induce damage to the salt matrix. Damage occurs when the deviatoric (shear) stresses are relatively high compared to the applied mean stress [4]. Salt damage manifests through time-dependent initiation, growth, and coalescence of microfractures. These processes lead to a bulk dilation of the affected rock, increasing the porosity and permeability of the salt to brine and gas flow. The extent of the DRZ surrounding mined salt openings has been measured directly at WIPP and elsewhere using extensometers and techniques such as sonic velocity, brine and gas flow properties, and laboratory analysis of cores. Point geophysical measurements have validated the geometry and rock properties predicted by numerical damage models [1]. These features and their measurements are discussed subsequently.

2.2 Room Closure

The test configuration described here would confirm the geophysical response of the test bed before, during and after the mining of the testing drifts. The bases for these proposed measurements draw from principles of salt deformation [1, 5].

A structural model prediction (Section 3) has been run to provide guidance for instrumentation placement. The calculation is based on a salt-creep constitutive model that tracks stress/strain history of the host rock [6]. Expected results from the structural calculation can be supplemented and corroborated by taking advantage of an extensive database of geotechnical measurements in salt. Geotechnical convergence observations taken at WIPP Panel 1 entry (Figure 1) illustrate a continuous twenty-year old salt-deformation record [7].

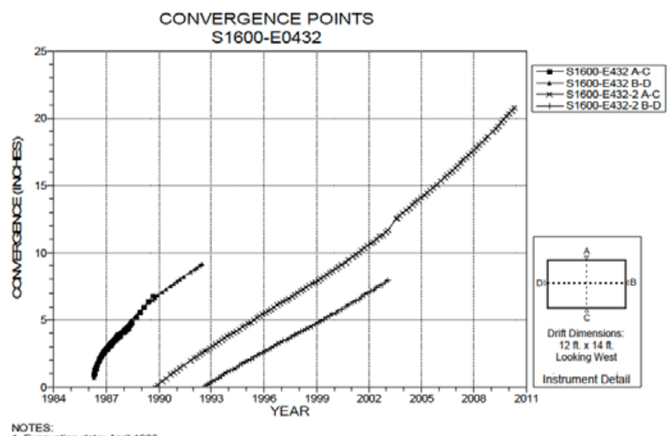


Fig. 1. Typical excavation closure measurements in salt.

Classical strain-time behavior for salt includes transient deformation that slows to a pseudo steady-state as the salt substructure evolves with time. Figure 1 does not account fully for closure magnitude of this particular drift because it does not capture early transient behavior that occurred during excavation. Model simulations can be used to provide a more complete deformation history, including hard-to-collect early-time data. In addition, the extent of damage around the excavation of Figure 1 is not discernable from these convergence measurements. By contrast, modeling results can be analyzed to include continuous predictions of DRZ extent and absolute displacement quantities.

2.3 Damage Evolution

Extensive laboratory creep data were evaluated in terms of volumetric strain resulting at various principal stresses [4]. Stress states that resulted in net volume increase (damage or dilation) were defined in terms of the first invariant of the traditional Cauchy stress tensor, I_1, and the square root of second invariant of the deviatoric stress tensor, J_2. These invariants are related to mean (or confining) stress and deviatoric (or octahedral shear) stress, respectively, and a clear delineation in the $I_1 - J_2$ stress space exists between conditions that cause dilation and those that do not, regardless of the type of salt or type of test considered [4]. A simple empirical stress-invariant model that separates dilating stress states from nondilating stress states is

$$\sqrt{J_2} = 0.27 I_1$$

This relationship is used to define a damage factor, with damage factor > 1 associated with points plotting above the line. Measurements of the DRZ around openings in salt have been made using various geophysical techniques [5]. Numeric predictions of the evolution of the DRZ replicate geophysical observations. The size and shape of the DRZ around an opening based on a stress-invariant criterion are comparable to the size and shape derived from sonic velocity studies and from microscopy of core damage [5].

3. STRUCTURAL ANALYSIS

Geomechanical model predictions are an integral part of field test planning because they demonstrate that the experimental concept is viable. Placement of gauges before excavation allows for evolutionary measurements that can be used to validate expectations from the models. This is particularly important in the realm of early-time creep phenomena where field data for validating geomechanical models are largely lacking. Prediction coupled with practical experience provides the bases for selecting instrumentation range, determining required accuracy, and establishing data quality objectives (DQOs), which quantify needed precision and accuracy based on how the data are to be used.

3.1 Geomechanics modeling

A preliminary two-dimensional isothermal structural analysis has been performed to determine the extent of the damage zone around a potential test drift and to aid in the design and placement of instrumentation [8]. We used the Adagio geomechanical module of the Sierra Mechanics [9] finite element code suite to simulate a two-dimensional cross-section passing through the mid-length of a nominal test drift oriented perpendicular to the long axis of the drifts. A full three-dimensional model would more accurately capture a final site and room configuration, but the two-dimensional model captures the essence of the generic problem. Material layering used in this example simulation is based on WIPP Room D stratigraphy, which can be considered typical for bedded salt.

3.2 Results

Geomechanical modeling can predict microfracturing using the stress-invariant criterion. The region with a computed damage factor > 1 at 887 days is colored in Figure 2. Multipoint Borehole Extensometers (MPBX) and fluid flow measurements can be situated to measure the effects of the DRZ using this type of information.

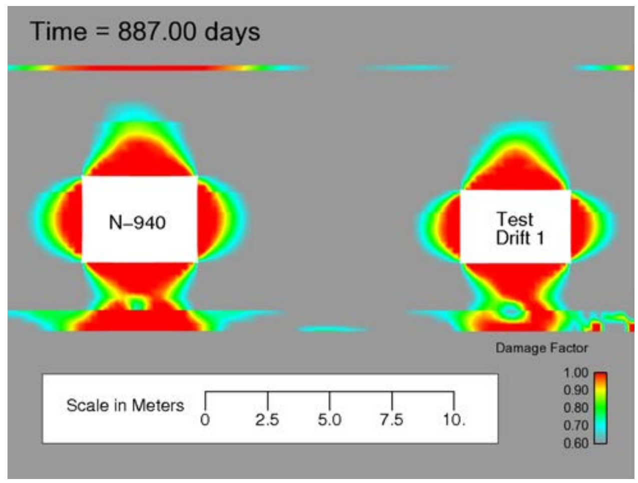
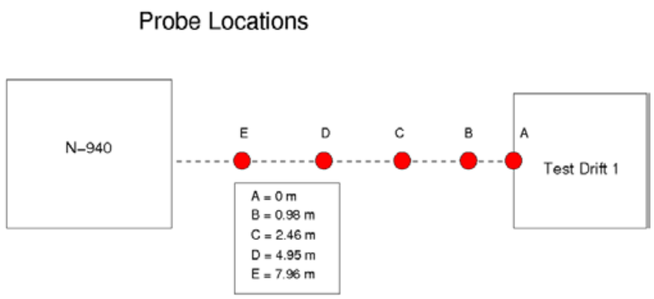


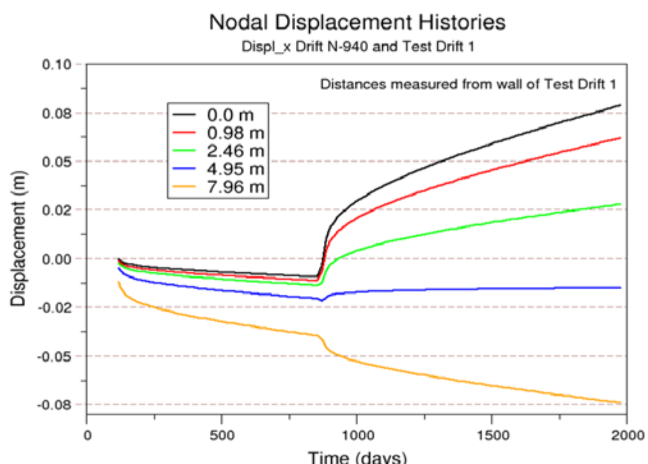
Fig. 2. Damage contours from geomechanical models.

To provide an estimate of the temporal change in the displacement field between the drifts, displacement through time was predicted along a horizontal line of displacement probes between observation drift N-940 and Test Drift 1 (Figure 3a). Time histories of the horizontal displacements at these nominal locations are shown in Figure 3b). A positive value of the displacement means the probe location is moving toward the test drift excavation. In this simulation, the probes are installed soon after excavation of observational drift N-940. At first, all probe locations would be moving toward N-940. The kink in the displacement history curves occurs when the test drift is excavated. Probe locations are analogous to anchor locations for a multipoint borehole extensometer installed in drift N-940. The probe locations are shown relative to Test Drift 1.

Based on these calculations, extensometer ranges and accuracy can be specified. For example, an anchor could be set at 0.5 m from the new excavation wall, with a measurement range of 0.10 m (nominally twice the expected displacement shown in Figure 3). The outer anchor would be set at about 5 m, which is approximately neutral between the two drifts. Displacement precision should be approximately 0.001 m (1 mm), which is 1% of range. Off-the-shelf extensometers are typically more sensitive than ± 0.001 m. Final arrangements and gauge selection would be determined by the Principal Investigator, but this example shows how model predictions can assist with establishing DQOs.



a)



b)

Fig. 3. Predicted temporal displacements as a function of position between observation drift N-940 and Test Drift 1.

4. BRINE AND GAS FLOW

We propose a complementary set of instrumentation for measuring deformation installed at two different times. The first instrumentation holes will be drilled before mining of the drifts (there are access drifts parallel and perpendicular to the testing drifts that will have already been mined). Proper placement of MPBX measurement points in these holes will allow test-drift deformation to be measured from the very beginning of test room mining, including the difficult-to-observe early transient deformation. After the test drifts are excavated, instrumentation will be placed into the salt from within each drift before additional in-drift test hardware or materials are brought into the working area. Drilling holes and placement of gauges radiating outward into the country rock can be executed relatively quickly. Wiring leads from instrumentation to data collection facilities located outside the testing drifts can be secured in small channels cut into the host rock for protection from ongoing in-drift activity.

Temperature and mechanical deformation measurements will be collected at corresponding locations to enable data collection for thermal-expansion compensation of the extensometers. Final design depths, ranges, and DQOs would be aided by final test site selection and preliminary thermal and geomechanical model predictions.

Permeability testing boreholes would be situated in the expected DRZ. The combination of MPBX displacement measurements and fluid testing will generate data to allow a correlation to be made between a one-dimensional strain level and a fluid flow state or properties. Intact geologic salt is essentially impermeable to brine or gas flow (permeabilities $<10^{-20}$ m^2). In its undisturbed state, the intergranular porosity of intact salt is quite low (≤1%), unconnected, and filled with saturated brine. Pressure within occluded pores would be equal to lithostatic pressure. Interconnected porosity, which can be created by salt dilation, is required to allow brine to flow under a stress or pressure gradient; this dilation does not exist in undisturbed salt at WIPP [3].

Beginning with excavation, the mechanical damage to salt in the DRZ (dilation) is associated with an increase in salt porosity, which results in desaturation of the DRZ. The brine that filled the very small undamaged porosity cannot expand to fill the larger damage-induced porosity. The increased porosity of salt in the DRZ is associated with a decreased air entry pressure, facilitating air to enter the DRZ from the mined opening. The porosity increase leads to an increase in the absolute permeability of the salt, but the relative brine permeability of the DRZ decreases due to the invasion of air into the newly created fracture apertures. Salt gas permeability increases due to the additive effects of increasing intrinsic permeability and increasing relative gas permeability. The combination of increased porosity (i.e., storage capacity), increased permeability, and the pressure gradient toward the excavation were explored numerically to match data collected during the WIPP Room Q brine inflow experiment [10]. These modeling results corroborated that mechanical effects (increase in porosity and permeability due to damage) control and drive the hydrologic system.

Figure 4 illustrates typical behavior of salt core during laboratory deformation and accumulation of damage, indicating how intrinsic permeability changes early during the deformation (associated with only a very small increase in porosity due to dilation), and how the geophysical observations of acoustic emissions and sonic wave velocity change with increasing deformation as well. The beginning of stage I in Figure 4 includes the re-consolidation of the sample by closing fracture apertures associated with accumulated damage to the core from extraction and handling. Permeability decreases during stage I, which does not occur during field observations of DRZ development. Increasing differential stress during the early laboratory test would be analogous to the significant differential stresses that develop around an excavation. During the deformation of a mined opening, late stage I and stage II of Figure 4 occur relatively quickly (within weeks or months), while stage III occurs over longer periods.

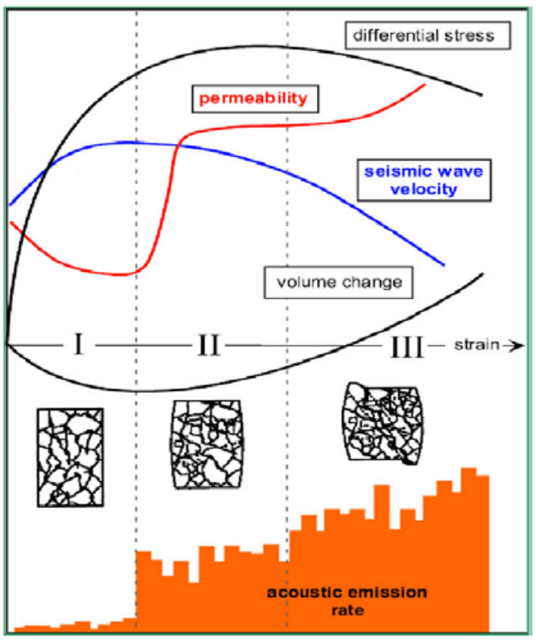


Fig. 4. Physical property changes in salt during typical deformation in laboratory testing [11].

Once the changes to the porosity, intrinsic permeability, and brine saturation have occurred, brine flows into the DRZ under the influence of gravity, pressure, and capillarity. This redistribution of brine is slower than the initial mechanical response of the system, which creates the DRZ and largely air-filled zone surrounding the excavation.

Depending on the method used to characterize the DRZ, it typically develops from 1-2 meters up to one excavation "radius" into the host rock. Characterization of the DRZ provides concrete information regarding the initial and boundary conditions for the drift. The DRZ can act as a source, sink, and pathway for brine and vapor moisture. Characterizing the spatial extent and temporal evolution of the DRZ around excavations provides boundary conditions for future activities.

4.1 Gas Flow

Laboratory and in situ testing programs at WIPP have characterized both brine and gas flow through the DRZ [3, 12]. In general, gas flow measurements are simpler to conduct than brine flow measurements in areas where the air entry pressure is low (i.e., the DRZ), and provide a good diagnostic for delineating the extent of the DRZ. Estimates of DRZ extent and shape from gas flow measurements are qualitatively similar to those predicted by geomechanical models and interpretation of cross-hole sonic velocity measurements. Gas flow rate into a short packed-off borehole interval can be measured at a specified working pressure. The test is relatively quick to conduct, and can be repeated across different intervals to assess the variability of the DRZ along the length of the borehole. Gas flow measurements will be made before during, and after excavation of test rooms to confirm initial absence of a DRZ and subsequently to confirm creation and evolution of the DRZ upon test room mining.

Gas is a non-wetting fluid, and will only displace brine (the wetting fluid) under relatively high pressures. Typical undisturbed salt has a pore structure that precludes gas displacing brine prior to reaching lithostatic pressure. Therefore gas flow measurements will essentially test only the air-filled porosity and relative gas permeability of the DRZ. Residual brine will remain in the DRZ, but this fraction of the porosity will be inaccessible to low-pressure gas. Attempting to make gas flow measurements at the far edge of the DRZ (where porosity is lower and therefore brine saturation is higher) or in areas where brine has flowed back into the DRZ, may result in gas displacing brine, which is a non-linear process that complicates test interpretation. Gas testing will essentially be used to quantify the extent of the DRZ, with some rough quantification of damage. High gas flow rates can be associated with macroscopic fractures and bedding separations, often located where creeping salt interacts with relatively brittle non-salt materials.

4.2 Brine Flow

Brine flow measurements are more difficult to make than gas measurements because brine is more viscous, and in a low permeability media, this contributes to very low or no flow in injection test configurations. Historic testing of brine permeability in boreholes was sometimes accomplished using a complex packer apparatus to minimize tool movement, measure borehole deformation, and accommodate high-pressure long-term tests [12]. Characterization activities proposed here do not envision complex long-term brine flow tests, but will measure brine pressure in boreholes before and after test drift mining. If salt permeability and brine saturation are both high enough, brine pressure is expected to stabilize readily (indicating a meaningful inter-granular pore pressure can be interpreted). When this occurs constant pressure tests will be conducted to estimate brine permeability. But unlike gas flow tests, if a brine flow test interval is too damaged or dilated (high intrinsic permeability but low brine saturation), the shut-in pressure will likely not stabilize, indicating the brine is displacing air in the DRZ porosity.

While brine will readily displace gas that is not trapped, the penetration of brine into an air-filled porous or fractured medium is also a non-linear process. These types of tests would be difficult to meaningfully analyze with linear well-test solutions developed for either brine or gas flow without significant simplifying assumptions of flow behavior around the borehole.

Interbeds comprised of non-creeping minerals typically exist within salt formations. In excavations similar to that proposed for this test configuration, such interbeds become highly fractured due to the extent of the DRZ and brittle material behavior. The WIPP Brine Sampling and Evaluation Program (BSEP) conducted from 1982 to 1993 included "water table" observations in vertical boreholes in the floor [13]. The BSEP investigations found brine readily flowed into boreholes completed in an anhydrite layer below excavations, especially at the intersection of large drifts. Recognizing the connectivity of the DRZ below the rooms, particularly where brittle interbeds are intersected, brine accumulation could be monitored in vertical boreholes. Based on prior experience, a relatively brittle stratum located beneath an excavation may act as a brine collection drain for the test drifts because of its stratigraphic location [14]. Since vertical boreholes provide a simple measurement opportunity, short pumping or purging tests may be conducted to estimate permeability of the brine-saturated damaged zone penetrated by these boreholes.

4.3 Data Quality Objectives

A quality scientific endeavor is predicated on sound application of the scientific method. In this look forward measurements include undisturbed conditions and transient characteristics during and after excavation. Such measurements would generally confirm the understanding of physical changes, while providing specific detailed boundary conditions for future field experiments. In addition, results of these measurements provide opportunities for validation of modeling techniques.

Because of extensive history in this type of experimental work, both in the U.S. and internationally, the basic material and geologic formation behavior of salt is well known. Undamaged salt is essentially impermeable, while minimal damage (volumetric strains as small as 0.01%) will increase permeability by 5-6 orders of magnitude. Reversing the stress state toward equilibrium and simultaneously reducing shear stress will heal salt fractures. Geomechanical simulations can track the stress state and post-process ratios of stress invariants for the damage contours as shown in Figure 2.

In a Test Plan, specifications for each instrumentation hole (size, orientation, depth, and drilling method) and each gauge (type, placement, accuracy and range) will be established along with a discussion of relevance of each measurement and other pertinent criteria. This type of information is prepared by the Principal Investigator and author of the particular Test Plan. External review is encouraged because there will always be trade-offs concerning data quality, time, budget, coverage, redundancy, and a basic instrumentation program. The external review will improve the overall quality of the test by incorporation of multiple perspectives.

Quantitative DQO information below provides examples of how the measuring basis is established. Firm quantities will be given in the reviewed and approved Test Plan. However, it is instructive to provide general rationale for DQOs here:

- Extensometers: ±0.01 strain or 1 mm. As noted in the text and from underground measurements in rooms analogous to the possible test drifts, roof-to-floor closure on the order of 100 mm could be expected. Within the rock mass, the minimum active length between extensometer anchors would be ~1 m. Therefore, an accuracy of 1 part per 100 or .01 strain is the appropriate resolution for the intended use.
- Host Rock Temperature: $\pm 1^{o}$ C. Variability within 1^{o} C is well within expected modeling accuracy and reflective of natural variability.
- Pore pressure: ~10% of measured value. A pore pressure resolution of 10% is comparable to pore pressure natural variability and pore pressure provides a boundary condition for modeling flow tests. Experience has shown that 10% uncertainty is sufficient to enable modeling fluid flow response where permeability is estimated in orders of magnitude.
- Brine flow in host rock: ~1 cc/day. Small-scale mine-by testing around a 1 m diameter borehole performed previously [15] showed that a flow of 1 cc/day using a constant pressure test configuration corresponded in that geometry to about 3×10^{-18} m^2 permeability. The undisturbed host rock permeability varies around 10^{-21} and 10^{-22} m^2 (and zero). Permeability measured in the range of 10^{-18} m^2 or higher can be expected if the rock mass has been mechanically disturbed.
- Gas flow: threshold only (flow or no-flow) at low working pressure
- Barometric-ventilation pressure: 0.001 psi. This is based on data taken from WIPP [ ] where pressure differential across bulkheads was measured. Pressure differentials in this range

could move appreciable volumes of ventilation through the DRZ.

- Scan frequencies of up to 1 Hz will be needed for some transient tests and during the mine-by because the change in fluid flow test interval pressure can be significant in a 1 second time interval.

5. CONCLUDING REMARKS

Creep deformation and evolution of damage around new excavations in salt significantly alter favorable characteristics of the virgin ground. This document describes modeling, testing, and measurement methods that can be used to capture early evolution of these changing characteristics.

Principal measurements make it possible to monitor geomechanical response and the associated changes in permeability. This progression will help establish boundary conditions for later activities conducted within the excavations. Pretest predictions are made of strain magnitudes, room closure, and margins of the damaged zone. In turn, data collected during the disturbed rock zone evolution will allow assessment of the predictive capability. Geomechanics modeling provides a basis for data quality objectives, which help define instrumentation requirements. Sufficient detail is provided to install gauges, conduct tests, and describe applicable functional and test-specific requirements. This type of forward thinking provides a means to reach and document consensus on all aspects of a test or experiment, including design, cost, schedule, interface controls, and data management.

REFERENCES

1. Hansen, F.D. and C.D. Leigh. 2011. Salt disposal of heat-generating nuclear waste. *SAND2011-0161*. Sandia National Laboratories. Albuquerque NM.
2. Johnson, K.S. and S. Gonzales. 1978. Salt deposits in the United States and regional characteristics important to storage of radioactive waste. Prepared for Union Carbide Corporation, Nuclear Division, Office of Waste Isolation *Y/OWI/SUB.-7414/1*, p. 13-38.
3. Beauheim, R.L. and R.M. Roberts. 2002. Hydrology and hydraulic properties of a bedded evaporite formation. *Journal of Hydrology*. 259(1):66–88.
4. Van Sambeek, L.L., J.L. Ratigan, and F.D. Hansen. 1993. Dilatancy of rock salt in laboratory tests, *International Journal of Rock Mechanics, Mineral Science & Geomechanics Abstracts*, 30:735–738.
5. Hansen, F.D. 2003. The disturbed rock zone at the Waste Isolation Pilot Plant. *SAND2003-3407*. Sandia National Laboratories, Albuquerque, NM.
6. Argüello, J. G. and J.S. Rath. 2012. SIERRA mechanics for coupled multi-physics modeling of salt repositories. in P. Bérest, M. Ghoreychi, F. Hadj-Hassen, M. Tijani (eds). *Mechanical Behavior of Salt VII*. London: Taylor & Francis Group.
7. DOE. 2012. Geotechnical analysis report for June 2010-June 2011. *DOE/WIPP-12-3484*. http://www.wipp.energy.gov/library/CRA/CRA-2014/References/Others/US_DOE_2012_Geotechnical_Analysis_Report_DOE_WIPP_12_3484.pdf
8. Holland, J.F. 2014. Mechanical and hydrological characterization of the near-field surrounding excavations in a geologic salt formation. *SAND2014-17822 R (Appendix D)*. Sandia National Laboratories, Albuquerque, NM.
9. Edwards, H.C. and J.R. Stewart. 2001. SIERRA: A software environment for developing complex multi-physics applications. In K.J. Bathe (ed.), *First MIT Conference on Computational Fluid and Solid Mechanics*, Amsterdam: Elsevier.
10. Freeze, G.A., T.L. Christian-Frear, and S.W. Webb. 1997. Modeling brine inflow to Room Q: A numerical investigation of flow mechanisms. *SAND96-0561*. Sandia National Laboratories, Albuquerque, NM.
11. Schulze, O., T. Popp, and H. Kern. 2001. Development of damage and permeability in deforming rock salt. *Engineering Geology*, 61(2-3):163–180.
12. Stormont, J.C. 1997. In situ gas permeability measurements to delineate damage in rock salt. *International Journal of Rock Mechanics, Mineral Science & Geomechanics Abstracts*, 34(7): 1055–1064.
13. Deal, D.E., R.J. Abitz, D.S. Belski, J.B. Case, M.E. Crawley, C.A. Givens, P.P.J. Lipponer, D.J. Milligan, J. Myers, D.W. Powers, and M.A. Valdivia. 1995. Brine sampling and evaluation program 1992-1993 report and summary of BSEP data since 1982. *DOE-WIPP 94-011*. Westinghouse Electric Corporation, Carlsbad, NM.
14. Kuhlman, K.L. and B. Malama. 2014. Assessment of contaminated brine fate and transport in MB139 at WIPP. *SAND2014-16153*. Sandia National Laboratories, Albuquerque, NM.
15. Knowles, M.K. and C.L. Howard. 1996. Field and laboratory testing of seal material proposed for the Waste Isolation Pilot Plant. *Waste Management Conference Proceedings.* Paper 7-01.

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