SAND2014-17822R

Sandia National Laboratories

Department of Energy Office of Nuclear Energy
Used Fuel Disposition (UFD) Campaign

Test/Activity Plan TP XX-XX (DRAFT)

Mechanical and Hydrological Characterization of the Near-field Surrounding Excavations in a Geologic Salt Formation

Project: 180682
Task 14.05

UFD WBS: 1.02.08.18
UFD Work Package: FT-14SN081805
UFD Level 4 Milestones: M4FT-14SN0818056 (Test Plan)
M4FT-14SN0818053 (Appendix D)

Rev. 0

Effective Date: September, 2014

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Sandia National Laboratories   U.S. DEPARTMENT OF ENERGY

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Revision 2
12/20/2012

APPENDIX E

FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.: Draft Report, Test Plan for Mechanical and Hydrological Behavior of the Near-field Host Rock Surrounding Excavations / M4FT-14SN0818056 / DRAFT rev

Work Package Title and Number: Salt R&D to Support Field Studies – SNL (FT-14SN081805)

Work Package WBS Number: 1.02.08.18

Responsible Work Package Manager: Kris Kuhlman
(Name/Signature)

Date Submitted

Quality Rigor Level for Deliverable/Milestone[2]	☒ QRL-3	☐ QRL-2	☐ QRL-1 Nuclear Data	☐ Lab/Participant QA Program (no additional FCT QA requirements)

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☒ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below

Name and Signature of Reviewers
Kris Kuhlman

NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the FCT Document Cover Sheet.*

NOTE 2: *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone. If QRL 1, 2, or 3 is not assigned, then the Lab / Participant QA Program (no additional FCT QA requirements) box must be checked, and the work is understood to be performed and any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

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1.0 DEFINITION OF ABBREVIATIONS AND ACRONYMS

DOE	Department of Energy
DQO	Data Quality Objective
DRZ	Disturbed Rock Zone
FCT	Fuel Cycle Technologies
MB139	Marker Bed 139
M&TE	Measuring and test equipment
psi	pounds per square inch
QAP	Quality Activity Plans
QAPD	Quality Assurance Program Document
SNL	Sandia National Laboratories
UFD	Used Fuel Disposition
WIPP	Waste Isolation Pilot Plant

2.0 REVISION HISTORY

This is the original version of this test plan. It was prepared in accordance with Sandia Fuel Cycle Technologies Quality Assurance Procedure FCT QAP 20-1 *Test/Activity Plans*.

3.0 PURPOSE AND SCOPE

The technical basis for salt disposal of nuclear waste resides in salt's favorable physical, mechanical and hydrological characteristics. Undisturbed salt formations are impermeable. Upon mining, the salt formation experiences damage in the near-field rock proximal to the mined opening and salt permeability increases dramatically. The volume of rock that has been altered by such damage is called the disturbed rock zone (DRZ). Creation of the disturbed rock zone or DRZ can enable formation brine to flow into the mined opening via increase permeability. Brine content is approximately ten times greater in domal salt than in bedded formations. The mechanical response to excavation initiates many important changes to the very favorable characteristics that exist in salt formations before excavation takes place. Investigations that utilize the underground for experimental activities would benefit greatly from the knowledge of initial, undisturbed conditions, the evolutionary changes imparted by excavation, and the boundary conditions extant when field activities are undertaken. Fortunately, the underlying basics of these mechanical and associated hydrological phenomena are understood and techniques for their measurement have been practiced in underground salt settings, including the Waste Isolation Pilot Plant (WIPP). This Test Plan sets out testing and measuring protocols to quantify conditions before underground space is opened and to measure the evolution of displacement, strain, damage, and permeability that occurs during and after excavation. The essence of this Test Plan would support virtually any type of field demonstration or test that involves room-scale excavation in a geologic salt formation.

Regulatory compliance of a geologic repository in salt will need to be demonstrated, in part, by credible representation of DRZ development and healing around panel and shaft seals because this zone of increased permeability can be a pathway for radionuclide movement. Understanding the development of the DRZ is essential to design and analysis of waste containment systems during the repository disposal/operational phase as well as to the design and evaluation of repository sealing systems to fulfill permanent closure functions.

This test plan is formulated based on the premise of having an underground test facility in a geologic salt deposit comprised of access drifts in addition to specially constructed test rooms where particular repository investigations or demonstrations can be conducted. The host-rock characterization program described in this test plan would begin from a minimally undisturbed state where instrumentation is installed at the periphery of test rooms *before* room mining begins, and track changes during mining operations, where stresses are redistributed and damage processes ensue.

The primary approach for characterizing the DRZ is by use of fluid-flow test boreholes and injecting gas or brine in the areas of interest where mechanical changes occur. This testing program will make deformation measurements at locations homologous to fluid flow measurements so that unambiguous correlations can be established between rock strain and permeability changes. The testing program will be sequenced to distinguish between temporal mechanical effects (immediate vs quasi-static deformation processes) and will use measurement techniques that are well established. The arrangement of instrumentation and measurement techniques allows establishment of initial (undisturbed or minimally disturbed) conditions, capture of the rapid transient response, and evolutionary monitoring as the salt creeps into the room. This test plan describes how to characterize the mechanical behavior and hydrologic response of a test room near-field host rock and thereby establish boundary conditions for any test or demonstration that might be conducted in the excavation.

Changes in the rock mass surrounding an excavation can also be detected and characterized using geophysical techniques including ultrasonic waves and electrical resistivity tomography (ERT). Such techniques have been used in the WIPP and elsewhere [Holcomb and Hardy, 2001; Jockwer and Wieczorek, 2008; Truskowski, et. al, 1993]. These techniques can be employed from boreholes in cross-hole configurations or from excavation surfaces. These techniques are used to qualitatively visualize the DRZ extent and do not quantify fluid flow capacity, which is the parameter of direct interest to repository performance assessment radionuclide release models. For this reason, these measurements are not included as part of this test plan, but they could be used to corroborate the fluid flow measurements.

Test methods described here are adaptable to essentially any testing configuration. In order to demonstrate a possible test layout for the initial issue of this test plan, a test layout comprised of two test rooms approximately 80’ long, 16’ wide, and 10’ high separated by salt pillars 35’ is assumed. The strata containing these rooms are assumed to be comparable to the waste disposal panels of the WIPP. Rooms with such dimensions would provide mechanical stability based on geotechnical data gathered at WIPP [DOE/WIPP-12-3484].

Fundamentally, an underground test facility in salt provides an opportunity to measure undisturbed permeability, which is expected to be almost unmeasurably low. Such a measurement would confirm this widely recognized salt property. Excavation perturbs the stress state and the static salt formation begins to deform into the opening. The process of mechanical deformation creates fractures in the proximity to the openings. Fracture damage creates a permeability that did not exist before, and the accessible brine moves down the hydrologic gradient toward the opening. Some of the brine reaches the walls of the opening and is evaporated by ventilation air. Some of the brine remains in the DRZ and flows by gravitational head below the excavation into void space there, which is created in the floor region by flexure. The brine below the floor is expected to migrate down any geologic slope of a bedded salt formation. The creation of the DRZ and its geometry and properties, as well as the availability of brine and its fate create initial boundary conditions of the underground setting regardless of the technical purpose for which an excavation is used. A detailed discussion of salt mechanical behavior and testing approaches is contained in Appendix A.

This test plan has two overarching goals. First, it presents an overview of the fundamental science embodied by the measurement configuration. This information will allow external review of the merits of the proposed investigations as well as internal integration of this series of measurements with whatever related testing activity might be under consideration. Second, it describes the activities in sufficient detail to enable an appropriately trained and indoctrinated technical team to implement the test program in the underground research facility. The general objective of these test activities is to characterize the mechanical and hydrologic boundary conditions associated with room excavations in an underground research facility. 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 of this test are as follows:

- Monitor rock mass deformation in the near-field around excavations sufficiently to confirm behavior consistent with previous measurements within geologic salt formations. This will include installing extensometers before mining.
- Monitor evolution of fluid flow properties in the host rock around the room sufficiently to characterize specific points in the damaged rock mass. Definition and explanation of rock damage is provided in Appendix A, and these fundamental properties of the salt formation can be predicted by calculation, monitored for confirmation, thus validating the computational simulation. 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 excavations will influence the ambient gas pressure measured in the near-field rock, which can lead to drying of the room surfaces and the DRZ.

4.0 EXPERIMENTAL PROCESS DESCRIPTION

4.1 Overall Strategy and Process

4.1.1 Test Configuration – Rooms and Boreholes

4.1.1.1 Test Room Layout

The location and configuration of generic test rooms assumed for this plan is shown below in Figure 1. Concerning stratigraphy, the room is assumed to be located above a non-halite deposit, comprised of something like anhydride or limestone that is much more brittle than the surrounding salt.

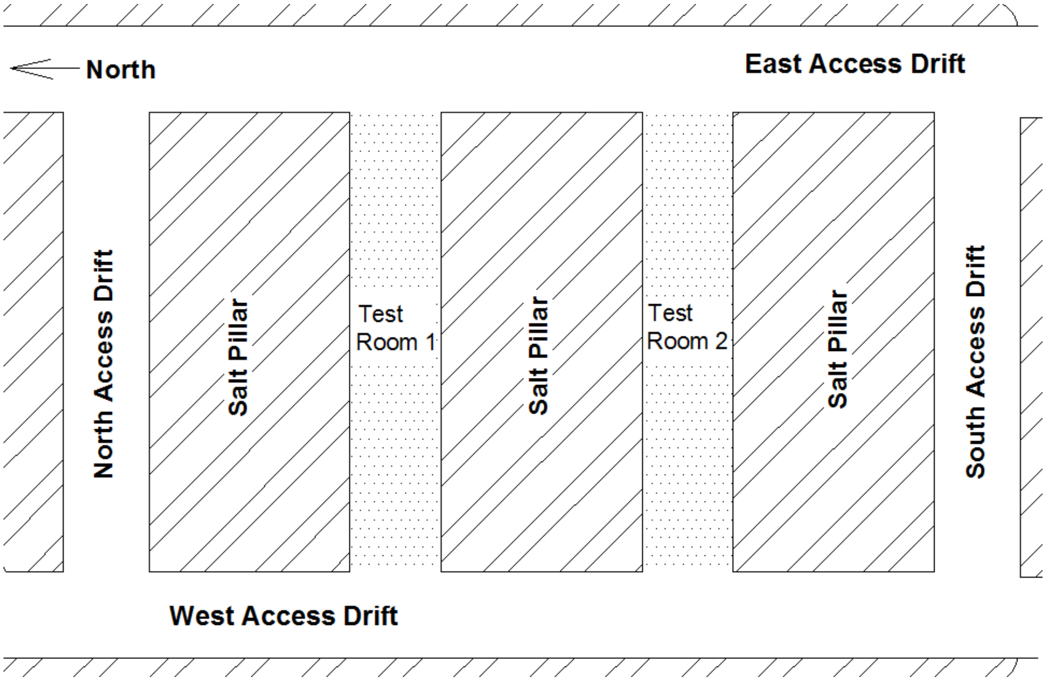


Figure 1. Configuration of access drifts and test rooms in a generic underground research facility.

4.1.1.2 Extensometer and Room Closure Gage Layout

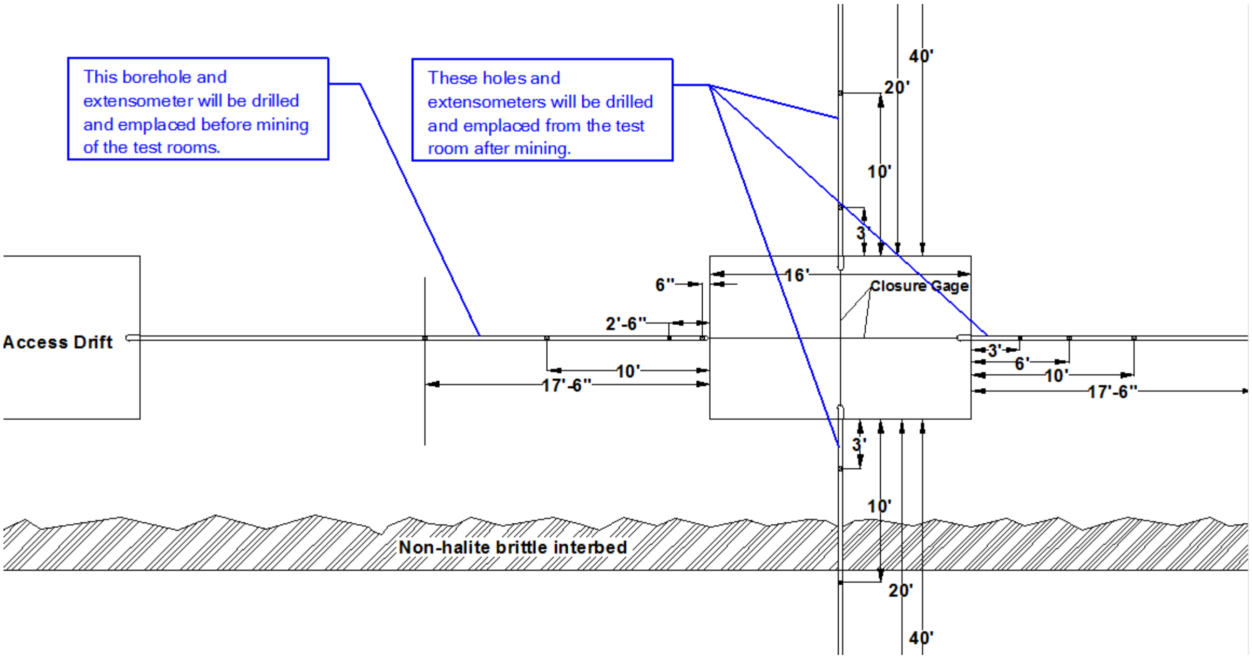
Four multipoint extensometers will be installed in 4 boreholes oriented perpendicular to the room axis. As explained below, some of these will be installed from the access drifts before mining of the test rooms. These instruments will be placed at the axial midpoint of each test room to minimize end effects. The 4 holes will be oriented vertically up, down, and horizontally - one into each of the adjacent pillars as shown in Figure 2; three of these holes be drilled from the room after mining. Each borehole will contain 4 extensometer anchors and the extensometer heads will be anchored at the borehole collar (where the borehole enters the rock mass). More detail about the extensometers in provided below in the Section 4.1.3.1. Borehole numbers and extensometer points of measure are defined in Appendix B

Borehole *Layout* and Appendix C

Gage *Identification and Layout*. Figure 2 is typical of both rooms mirrored symmetrically about a plane bisecting the middle pillar between the two test rooms. The boreholes that enter the outside pillars from the access drifts located to the north and south of the test rooms will be drilled and the extensometers installed and activated prior to mining of the test rooms. This will be done to establish initial conditions and enable monitoring of deformation during mining.

Figure 2 also shows two room closure gages spanning the test room width and height. These gages will be collocated with the extensometers to the extent practical and will be installed after mining of the test rooms. Function of this system requires an unobstructed line-of-sight between a laser and a target. More detail about installation of these gages is provided in Section 4.1.3.1. Closure gage identification numbers and positions are defined in *Appendix C*

Gage Identification and Layout.



This borehole and extensometer will be drilled and emplaced before mining of the test rooms.

These holes and extensometers will be drilled and emplaced from the test room after mining.

Figure 2 Rock Mechanical Deformation Gages – Extensometers and Room Closure Gages.

4.1.1.3 Fluid Flow Test System Layout

Measurements characterizing the fluid flow properties in the near-field rock surrounding the test rooms are essential to establish hydrologic as well as mechanical boundary conditions. The near-field rock will be instrumented with fluid flow test systems as shown below in Section 4.1.3.2. Each room will have 6 measurement intervals located in boreholes in the rock mass that is predicted to become damaged upon creation of the room. These measurement intervals will be created in the boreholes by isolating the bottom portion of each hole using a pressurized packer (depicted by solid black portions near the end of the boreholes illustrated in Figure 3). Test interval measurement locations in the salt will be homologous to zones of extensional strain monitored by the extensometers. Fluid flow behavior can then be monitored simultaneous with rock strain measurements in the case of the extensometers placed prior to mining (the extensometers originating from the access drifts). In addition to fluid flow measurements in the proximal salt, a borehole could be situated to measure fluid-flow response of proximal non-halite interbeds as shown in Figure 3. Measurements made in such interbeds can indicate the extent of floor heave (or roof sag if the interbed is above the room) toward the excavation. The phenomenon of floor heave and roof sag has been observed extensively in salt mining operations. As this bed is fractured, void space is created within the bed. Such fractures can be a sump for brine moving by gravity. Borehole identification numbers and drilling information is provided in Appendix B.

The fluid flow test boreholes will be nominally 2” diameter with test intervals ~18” long located to approximately straddle the centroid of the damaged zone (see APPENDIX A

Technical *Background Related to Salt Mechanical Deformation and Test Methods*) for more information about the damaged rock zone. The well bore needs to be smooth to promote a seal between the inflatable packer elements (made of a rubber) and the borehole wall. Both gas and salt saturated brine will be used as test fluids. In the gas test intervals, pressure fluctuations as a result of barometric pressure changes may be monitored if the permeability enables communication with the room air pressure. Relative humidity measurements could also be made in these intervals if this measurement is useful to establishing room boundary conditions.

The test method for brine completions calls for allowing the pressure in the borehole to equilibrate with the far-field pore pressure of the rock before mining or other activities. Because the rubber elements of the packers are compliant and flex in response to pressure changes, substantial time can be needed to allow equilibration to occur. The time to equilibrate will be reduced by attaching noncorrosive ballasts below the packers in the test intervals to reduce the fluid volume. The test intervals can be interrogated using either constant pressure or constant volume procedures. Testing or monitoring can occur before, during, and after mining. Because the rock permeability prior to the mining is believed to be low as found in previous measurements made in the far-field rock mass, active injection or withdrawal tests are not planned for this period; only pressure monitoring will occur. Fluid flow gage numbers are provided in Appendix C.

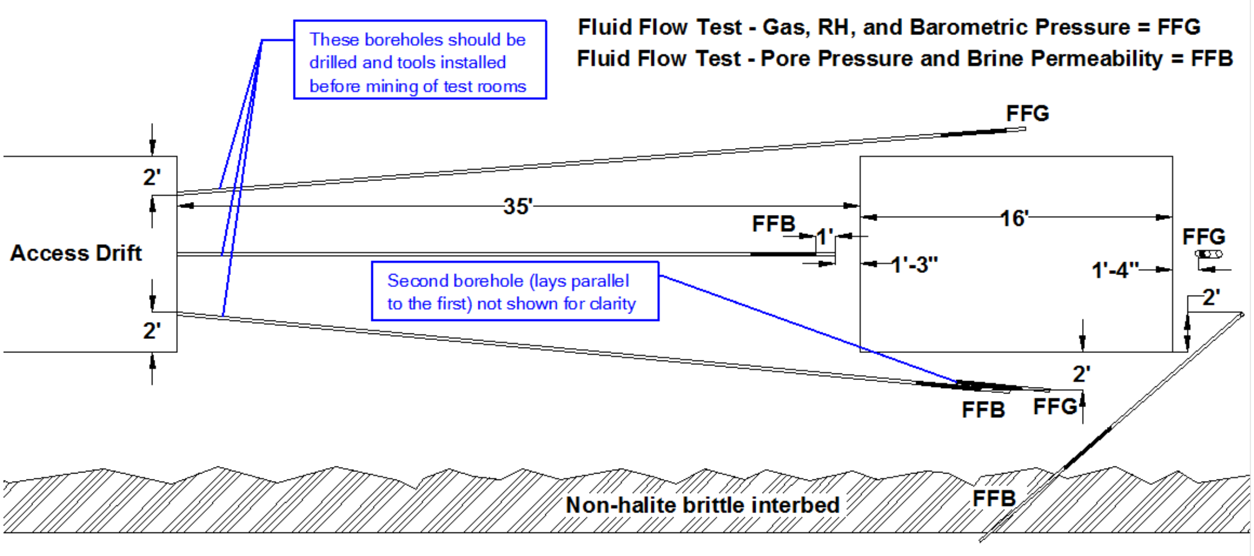


Figure 3 Layout of Fluid Flow Test Systems Around Typical Test Room

4.1.1.4 Barometric Pressure Gages

Barometric pressure gages will be used to monitor pressure in the drifts before excavation and eventually within the test rooms. Initially, one gage will be located in the west ventilation drift, one in the east ventilation drift. After excavation, barometric gauges can be placed in the rooms, as appropriate. Barometric pressure gages can also be connected to the gas-well completions to record pressure variations where the rock mass is in communication with the ambient atmospheric pressure. Gage numbers are provided in Appendix C.

4.1.2 Instrumentation Installation, Mining, and Testing Sequence

As described in Appendix A, substantial changes to the rock mass occur proximal to a mined excavation during mining. Simultaneous monitoring of mechanical response and its effect on hydrological properties has not been done before at the room scale. Such observations will enhance the understanding of the relationship between mechanical response and hydrological properties. For this reason, the testing and monitoring systems described above should be installed before mining. For a single test room, this includes one extensometer and all of the fluid flow test systems, which can be installed from the access drifts. Additional or redundant measurements would be better for confirming behavior and validating models, but such measurements are relatively costly, so only a single measurement is described in this test plan. If changes to the number of measurements are recommended during review, the test plan will be revised accordingly. Making these installations prior to mining will require proper sequencing of drilling schedules, instrument installation, assembly of data collection systems and management of operations logistics.

The fluid-flow test systems will need 60 to 90 days to equilibrate with the rock mass pore pressure, but could be emplaced, equilibrated, and tested well in advance of mining. Extensometers could also be installed essentially any time in advance of mining. Based on experience, the scan rate should be set to ~4/day when these systems are equilibrating.

After pre-mining instruments have been installed and reached steady state (equilibrium), test room mining can proceed. During this time the scan rate on the gages should be increased to about 1 per minute when mining anywhere in the test rooms, and 1 per second when mining is within ~20 feet of the monitoring gages. The response of the gages will be monitored and scan rate adjustments can be made as needed. The process of excavation in proximity to measurement gages is referred to as a "mine-by". During room mining, lithostatic stresses in the rock are redistributed. For this reason, when the mine-by is occurring, the packers will be shut-in so that if the rock and borehole dilate, the packer can increase in volume, maintaining the sealed test interval, but the pressure can adjust commensurate with the changes in host-rock stress.

When mining of the rooms is complete and the pre-mining gages have reached steady-state once more, scan rates can be reduced back to ~4/day. Active injection tests should be conducted on the fluid-flow test systems to measure permeability changes as soon after mining as practical. It is presumed, based on experience, that initial measurements after mining capture the state in the early transient creep, perhaps when relatively little deformation has occurred. For the gas completions, either constant pressure or constant volume (shut-in configuration) can be used to measure fluid flow potential. Brine completions will be tested in a constant pressure injection test configuration.

After mining, drill rigs can be deployed inside the test rooms, holes can be drilled, and the three remaining extensometers can be installed from the test rooms. If desired, barometric pressure gages can be installed in the room when convenient.

4.1.3 Test Equipment

A variety of measurement systems will be used to make the measurements described above. These systems will often be supported by instruments that calibrate or confirm operation. These measurement systems are described below. The usage of these systems will follow activity/project specific procedures . These procedures will typically include data forms to record associated data taken during specific test activities or at the time of gage installation following a prescribed format. Examples of data include details of where extensometer anchors were actually set and what pressures were established during the conduct of fluid flow tests.

4.1.3.1 Rock Mass Deformation

These measurements are made using multi-point borehole extensometers. Each borehole will contain 4 extensometer anchors and the extensometer heads will be anchored at the borehole collar (where the borehole enters the rock mass). Each hole will be 4” in diameter to accommodate the anchors and connecting rods. The anchors will be secured to the borehole wall using copper bladders inflated using vegetable or some non-hazardous oil. Pressure is retained in the bladders by use of check valves on the inflation lines. The extensometer heads are anchored at the borehole collar. Extensometer anchor heads may be recessed into the rock if their protrusion into the room conflicts with other operations, but this requires over-coring of the borehole by as much as 24” using an 8” core barrel. Inside the test room, such an installation precludes measuring the response of the first 24” into the rock surface, the region expected to strain the most. The heads will also be secured to the 4” diameter hole using inflatable bladders.

Room closure measurements will be made using laser distance sensors with a laser located on one room surface (wall or back for example), and a target on the opposite surface (opposite rib or floor) with an unobstructed line-of-sight between the laser and the target. A measurement is made by activating the laser, which is sighted on the target, and measuring the time taken for the reflected laser to return to a sensor located with the laser. Hardware needed to mount the closure gage will consist of mounting brackets that will be attached to the rock surfaces using mechanical anchors. This measurement could be obstructed by other test equipment in the room, in which case layout alterations will need to made.

4.1.3.2 Fluid Flow Testing

The fluid flow tests will be facilitated by placement of a rubber element packer, nominally 1 m long, near the bottom of 2” holes terminating in the target rock mass. A single stainless steel tube will be used to sense pressure and move fluid into or out of the test interval. The tube needs to be large enough so that pressure losses due to flow friction are not significant relative to the measurement being made. For these low-flow measurements, a ¼” tube is sufficiently large. A typical fluid flow control and measurement system is depicted in Figure 4, which is for a brine test system. The fluid flow control manifolds and along with pressure transducers will need to be assembled and tested by Sandia.

Bottled nitrogen can provide the driving pressure for packer inflation or test interval pressurization. In the gas test completions, nitrogen is used as the working fluid. After mining, injection or withdrawal tests will be made using a separate system that ties into the three way valve located above the test interval pressure transducer. The separate system will be employed specifically to measure flow rates under constant pressure conditions. These test systems will have an independent data collection unit to enable scan rates to be set independent of the long term data collection unit.

The packer pressure is generally maintained about 200 psi above the test interval pressure. The pressure differential between the packer and the zone should be at least 120 psi based on past experience with this type of system, but this is a function of the packer stiffness and smoothness of the borehole wall. It is conceivable that the packer could induce mechanical damage to the formation through over pressure, so the packer pressure needs to be as low as possible while allowing confidence that there is not leakage from the test interval. Characterization to determine the pressure differential where leakage could occur should be conducted in test pipes prior to field deployment.

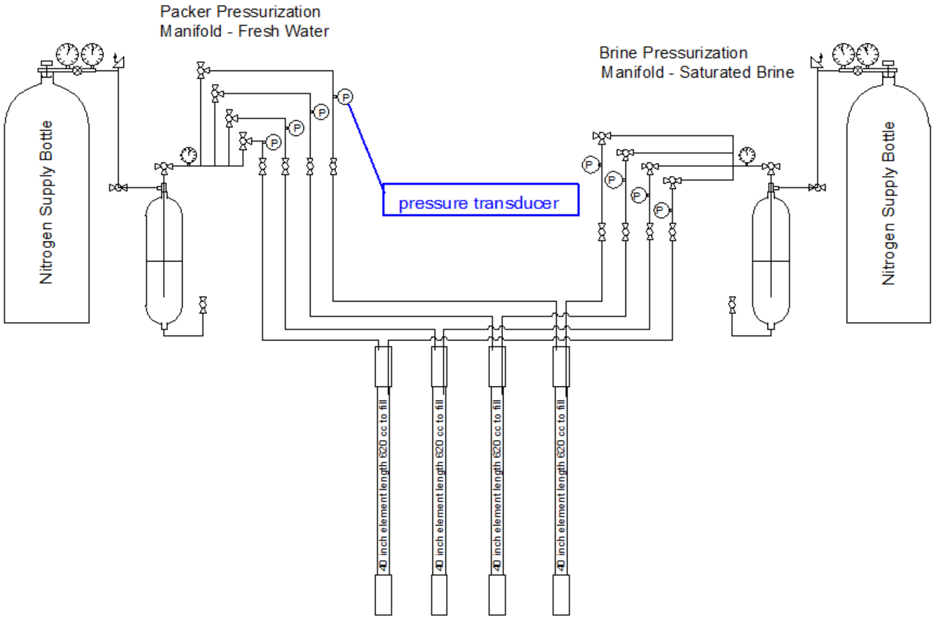


Figure 4 Four packer fluid flow control test system.

4.1.3.3 Barometric Pressure Gauges

Barometric pressure gages will be used to monitor pressure in the drifts, excavated rooms, and possibly in the DRZ. The gages to be used could be similar to those used previously in the WIPP at the Room Q test where pressure differentials between the ventilation drift and the test room were monitored.

4.1.3.4 Support Equipment

The fluid flow tests will employ many pressure transducers that need to be calibrated. Calibration of these gages will be accomplished by comparison to a pressure standard. A pressure standard should be procured to enable calibration or calibration confirmation to be performed at the test facility. Fluid-flow test pressures (including the packers) could be as high as lithostatic pressure.

Mass scales or balances with a resolution in the range of 0.01 grams will be needed for calibration of the brine injection system, which is accomplished by measuring brine mass and correlating it to pressure change. Proper function of such balances is typically confirmed before each use with a set of calibration weights. Balance calibration checks will be performed daily or prior to usage, using weight sets traceable to the National Bureau of Standards, which, in turn, are certified as accurate by the SNL Calibration Laboratory. Calibration checks will be recorded in balance calibration forms.

The location of boreholes relative to the excavation is important because the data collected will be evaluated as a function of position. For this reason, a tool and procedure will be developed to confirm borehole locations. This procedure is to be accomplished using a laser pointer that can be placed in the borehole, in alignment with the borehole, and sight back on the drill-hole survey back reference (typically a nail in the opposing face). Deviations from planned alignment can then be documented and measurements referenced to an “as-built” position.

4.1.4 Critical Variables

For the extensometer measurements, the critical variable is the relative movement between two anchors – and in this particular configuration, it is the two anchors located nearest the test room in the extensometers placed prior to mining. The displacement measurement is accomplished with a vibrating wire gage where the resolution is “infinite”, which means the transducer is fundamentally an analog output. Previous experimental work and long-term geotechnical monitoring can provide a reasonable estimate of deformation measured from within rooms of many widths. The application here is slightly more complicated than previous measurements because we will measure *all* the transient strain, whereas typical geotechnical measurements are able to collect only the late transient and early steady state. Therefore, extensometer anchor locations should be based on modeling, where quantitative estimates of the complete stress-strain behavior can be made. This calculation will provide additional benefit to salt science because it involves prediction and confirmation. Capability to perform requisite modeling has been developed that accounts for creep and deviatoric stresses that cause damage (for example Munson, et al., 1988).

For the fluid flow measurements, pressure in the test interval is the key variable. The test interval will be pressurized with gas or brine prior to mining with a pressure of ~500 psi (the needed pressure will be a function of ambient pore pressure and permeability). The amount of brine introduced to these completions will be minimized by the use of stainless steel ballasts in the test intervals. Concurrent with and after mining, this pressure is expected to fall precipitously (hundreds of psi in minutes or hours depending on the location of the mining [Jensen, et al. 1993 and Stormont, et al. 1990]). This observation of pressure drop confirms the increase in connected porosity and/or an increase in total porosity. After mining, as noted above, the test intervals will be actively tested, typically by injecting fluid at a pressure slightly above the formation pressure in the case of brine, or above the gas threshold entry pressure in the case of gas. Quantifying the volume of injected fluid is fundamentally made using pressure transducers, and the pressure measured is well within the range of accuracy of the transducers. More will be found on this topic in the discussion of data quality objectives in Section 4.3.2.

4.1.5 Procedures to be Used or Developed

Procedures needed to be developed to carry out this work are listed here. The need for additional procedures may become evident during implementation once operations are underway. These procedures will be activity specific procedures and will be created in accordance with FCT QAP 5-1 *Implementing Procedures*. They will be reviewed in accordance with provisions of FCT QAP 6-1 *Document Review Process*. They will be issued for use and controlled following FCT QAP 6-2 *Document Control*.

4.1.5.1 Test Bed Preparation Procedures

The following procedures will need to be developed in preparation for measurement system installation:

- Surveying borehole location prior to drilling
- Surveying borehole straightness
- Confirming the function of the borehole alignment survey tool
- Borehole alignment as-built survey (relative to planned alignment after drilling)
- Grouting of collars, rock mass thermocouples, or borehole casing
- Management of ES&H concerns with working in an underground research facility

Procedures may be developed to include several of these needs, and if certain elements are not conducive to a formal procedure, techniques employed will be recorded in a scientific notebook following FCT QAP 20-2 *Scientific Notebooks*.

4.1.5.2 Extensometer Related Procedures

The following procedure will need to be developed for installing and connecting the extensometers to the data collection unit.

- Installing and activating multi-point borehole extensometers

4.1.5.3 Fluid Flow Equipment Procedures

The following procedures will need to be developed for conducting the fluid flow tests.

- Building and leak checking fluid flow test equipment
- Installing brine completion test system
- Preparing synthetic brines for fluid flow experiments in a geologic salt formation
- Installing gas completion test system
- Calibrating pressure gages for the fluid flow test equipment
- Building and calibrating the fluid flow data collection system
- Use of laboratory balances and scales
- Operating the data collection system for the fluid flow test systems
- Calibrating the brine flow test tool
- Conducting a constant pressure injection test using the brine flow test tool
- Conducting gas flow testing of gas completion using the gas flow test tool
- Electronic and manual data management to ensure protection, retention and submittal of data

Testing of this type has been completed previously under rigorous Quality Assurance guidelines. Where practical, procedures previously used will be updated and made current. If certain activities or operations are not conducive to a formal procedure, activities employed will be recorded in a scientific notebook.

4.1.5.4 Barometric Pressure Related Procedure

The following procedure will need to be developed for installing and connecting the barometric pressure gages to the data collection unit.

- Installing and activating the barometric pressure gages

4.1.6 Prerequisites and Special Controls

To control experimental operations and to ensure objectives are achieved, the following preparations and prerequisites are planned.

- Prior to taking any of the above measurement systems to the underground facilities, the gages must be calibrated to an appropriate standard. Calibration confirmations can be conducted underground for some of the fluid flow test equipment if needed.
- Prior to installing any gages, the boreholes into which they are installed need a location, alignment, straightness, and depth survey.

Prior to room mining starting, the data collection system scan rate needs to be properly set and all of the measurement systems need to be confirmed as working unless other provisions are made.

4.1.7 Identification of Known or Expected Errors

Errors and uncertainties known to exist with the measurement systems include those associated with transducer accuracy. But this error is typically well below the data quality objectives. As-built instrument location is uncertain, but the uncertainty can be reduced to acceptable levels based on borehole survey data taken before and after drilling.

With respect to the fluid flow measurements, significant uncertainty comes from the fact that what is actually measured is the mass or volume of fluid injected into a borehole through the test interval tubing. Once the fluid enters the test interval, there is no tracking where it actually flows and it could flow in an isotropic homogenous geometry, or it could all flow into a single small fissure. Data interpretation methods require that an analyst assumes a flow geometry.

Another uncertainty that must be recognized and accounted for is spatial variability that exists in all natural geologic deposits at multiple scales. When a measurement is made at a given point, there is uncertainty associated with how representative that measurement is compared to the volume of rock that is the target of the measurement. In other words, if one makes a single measurement of rock mass deformation in the rib of the room while the room is being mined, how representative is that measurement compared to other locations along that rib, or in the opposite rib, or all other rooms in the test series, or even all rooms in the mine? Recognizing these limitations is essential to understanding the engineering significance of the data. This uncertainty can be used as a technical basis for determining the level of measurement redundancy.

4.1.8 Compatibility Between Data Collected and Modeling Parameters

For the measurements made for these tests, the parameters measured are those that can be directly extracted from predictive models. For example, for the fluid flow boreholes, the pressure signature as a function of time is what is measured, and pressure as a function of time is also what is predicted by the fluid flow models. The same can be said for the extensometer data. Deformation is monitored and deformation is directly predicted by the constitutive models used. A limitation associated with deformation is that it is measured in a single direction, but in the rock mass, deformation is a three dimensional process. The three-dimensionality of the underground setting is mitigated by placing the measurement gages at the point of symmetry and excavating a room that is long with respect to its other dimensions. If other geometries would be of interest, the simulations can readily be run in 3-D.

4.1.9 Records Retention

Records generated as a result of fielding this test plan shall be checked and verified to be complete and accurate in accordance with procedure FCT QAP 6-1 *Document Review Process*. Such records shall then be filed and retained following a records retention procedure.

4.1.10 Coordination with Other Organizations

Implementation of the test activities described in this test plan will rely on the cooperation and support services provided by a number of organizations. The details of roles and responsibilities is a function of the administrative and operations infrastructure of the underground facility and will need to be worked out when a test location has been selected. Organizations likely needing to participate are discussed here:

Sandia Primary Standards Lab (Center 02540) – for gage calibration services: Gages used in these tests need to be calibrated and controlled in accordance with procedures to control measuring and test equipment. Calibration of many of these gages may be done by Center 2540. For some of the gages, standards may be retained at the test location to enable calibration to occur there. For other gages, Center 2540 may need to certify that gages procured from outside vendors have valid calibration certifications.

Test Coordination Organization – for field support services: Related activities such as surveying of boreholes before and after drilling, oversight of drilling activities, and coordination and movement of scientific equipment into the underground will be facilitated by this organization. In addition, depending on how various tests associated with the test effort are structured, a central coordinating organization may provide data collection services for electronic gages where data are collected on predictable schedules at a frequency of a few times per day. All of the gages discussed in this test plan may rely on such a data collection system for primary (rock mechanics) or supplemental data collection (fluid flow testing).

Managing and Operating Contractor of Underground Facilities – for field services: The mining of test rooms, provision of compressed air, electrical power, lights, and ventilation will be provided through this organization. They will also lay out the instrument holes by survey, drill the holes, and grout borehole collars where needed. This organization will be controlling access to the underground, moving equipment underground, and ensuring field work activities are within facility operating limits. They will also make the necessary checks to confirm that all test activities are permitted within the operating constraints of the facility regulatory permits. Underground preparation activities (mining, drilling, and utility installation) will need to be coordinated and confirmed by scientific organizations as not adversely affecting technical test objectives.

Modeling Support Organizations – for technical input: Detailed technical input will be provided by scientific organizations involved with nuclear waste management programs. These organizations may not be collocated at the test facility.

4.2 Sample Control

There are currently no plans to retain physical samples of anything described in this test plan. If samples are collected, they will be retained, stored, and managed following FCT QAP 13-1 *Control of Samples and Standards*.

4.3 Data Quality Control

4.3.1 Pretest Modeling

Modeling of the phenomena to be measured in the test is essential to enable selection of appropriate gages and proper layout geometry for measurements. An important use of pre-test predictions for this test is predicting the damaged zone extent using a total stress vs deviatoric stress criterion as discussed in APPENDIX A

Technical *Background Related to Salt Mechanical Deformation and Test Methods*.

When the bounds of the damaged zone are established, placement of the fluid flow test completions can be confirmed. Placement of extensometer anchors will also be based on structural modeling predictions. Strain and deformation measurements proximal to fluid-flow test zones are key to interpretation of structural response and its relationship to permeability. Gage placement will be optimized to measure strain in the region where the fluid-flow tests are conducted.

It would be possible to estimate Data Quality Objectives (DQOs), configure drill holes, place gages, perform permeability tests, acquire deformation data, and otherwise undertake these test objectives without the benefit of state-of-the-art modeling. However, confirming an ability to model the evolution of the salt repository setting is essential to design, analysis and performance assessment for nuclear waste disposal. Therefore, this test effort is an appropriate opportunity to predict evolution and validate code capability. Modeling provides a two-way benefit: it serves as a basis for establishing DQOs, while measurements made in conjunction with excavation serve to validate the modeling capabilities. Modeling also allows estimates of early transient response and predicts the complete deformation history of the underground evolution.

A geometrically simple 2-D model is being developed to support developing DQOs as discussed in

Appendix D

Geomechanical *Modeling of Test Drifts*.

4.3.2 Data Quality Objectives

DQOs are noted below pending structural modeling results. A brief justification is also provided.

- 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 (see Appendix A). Within the rock mass, the 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: +/- 1^{o} C. Variability within 1^{o} C is well within expected modeling accuracy and reflective of natural variability of rock properties that control temperature.

- Pore pressure: ~10% of measured value. The pore pressure resolution of 10% is for two reasons:

  1) This is comparable to pore pressure natural variability measured in in previous tests,

  2) The pore pressure provides a boundary condition for modeling flow tests. Experience has shown that 10% uncertainty is sufficient to enable a good boundary for modeling the 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 showed that a flow of 1 cc/day using a constant pressure test configuration corresponded in that geometry to about 10^{-20} 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^{-20} 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 pressure can be significant in a 1 second time interval.

4.3.3 Measuring and Testing Equipment (M&TE)

A calibration program will be implemented for the work described in this test plan in accordance with an appropriate measurement and test equipment (M&TE) control program. This calibration program will meet the procedural requirements for: (1) receiving and testing M&TE; (2) technical operating procedures for M&TE; (3) the traceability of standards to nationally recognized standards; and (4) maintaining calibration records. Spreadsheet data and other computer based data handling will follow FCT QAP 9-1 *Analysis*.

4.3.4 Data Collection

Data collection procedures are specific to individual instruments or systems. Details of the data acquisition for a particular instrument will be provided in activity specific procedures or the user’s manual for that instrument or system. For each piece of equipment that will generate data, a data form shall be created. Any data acquired by a data acquisition system will be attached directly to a data collection form or compiled in separate loose leaf binders with identifying labels. If the instrument or system collects data electronically, copies of the data disks will be submitted to a records archive following records management and retention procedures. If possible, data files may be transferred to portable/removable media for submittal to the records center. For instruments that do not have direct data printout, the instrument readings will be recorded directly into data forms to be transferred as soon as practical to the records center after receiving a technical review in accordance with procedure FCT QAP 6-1 *Document Review Process*.

Data forms associated with specific equipment and procedures will be the main method of manually recording data. The use of scientific notebooks is discouraged for testing and measurements described here because the activities are designed for standard data collection methods that can be formalized in data collection forms. Notebooks can be used to record daily activities with respect to test implementation (a record of time and activities). Where scientific notebooks are used, quality control of the notebooks will be established by procedures described in procedure FCT QAP 20-2 *Scientific Notebooks*. Methods for justification, evaluation, approval, and documentation of deviation from test procedures or establishment of special prepared test procedures (in the field) will be documented in scientific notebooks where appropriate.

4.3.4.1 Manual Data Collection

As noted above, some data will be collected manually on data forms associated with activity specific procedures. This could include packer and test interval set pressures, and times when fluid flow tests were started, stopped, or otherwise conducted. These data forms, once filled out will be verified as complete and accurate in accordance with Procedure FCT QAP 6-2 *Document Review Process* and submitted to Sandia Records as soon as practically achievable. The goal will to have such checks and submittals of data occur within 24 hours of data collection.

4.3.4.2 Electronic Data Collection

Data from extensometers and fluid flow tools will be collected by an automated data acquisition system while monitoring steady-state conditions prior to mining. This system should monitor all gages simultaneously. A second separate and portable data collection system will also be used while conducting fluid flow tests after mining where such tests are conducted on a single test interval at any given time. Data from this system may be collected on removable media. The movement of data from underground to the records center, data transfers, and custody of these data will be controlled using appropriate data management procedures that will preclude the data from being lost or corrupted.

4.3.5 Data Collection Software Qualification

As noted above, a portable data collection system will be developed for short duration fluid flow testing where scan rates can be easily adjusted real-time. A separate data collection will be used to monitor all the instruments, but at a low scan rate of ~4 scans/day. Both systems will have software written to control data collection and this software will be controlled and qualified in accordance with software management and control procedure to ensure the software is functioning in accordance with design intent. .

5.0 QUALITY ASSURANCE

5.1 *Quality-Affecting Activities*

Activities described in this test plan are quality affecting. Data and observations made in these studies are expected to be used in repository design considerations and repository performance predictions.

5.2 *Quality Assurance Program Description*

Activities are conducted in accordance with the requirements specified in the Fuel Cycle Technologies (FCT) Quality Assurance Program Document (QAPD).

5.3 *QA Procedures*

The Quality Activity Plans (QAPs) and procedures that are expected to apply to work performed under this test plan include:

- FCT QAP 2-1 Qualification and Training,
- FCT QAP 5-1 Implementing Procedures,
- FCT QAP 6-1 Document Review Process,
- FCT QAP 6-2 Document Control,
- FCT QAP 9-1 Analysis,
- FCT QAP 13-1 Control of Samples and Standards,
- FCT SP 13-1 Chain of Custody,
- FCT QAP 20-1 Test Plans, and
- FCT QAP 20-2 Scientific Notebooks.

A complete discussion of the integration of these procedures under governing quality requirements is given in

Appendix E

Flow-down *of Quality Assurance Requirements*. Modification to these procedures may be required during testing activities following FCT QAP 6-1 and 6-2. Such modifications will not be reported as non-conformances that require corrective action.

5.4 *Manufacturers QA Procedures*

Test equipment manufacturers’ QA procedures will not apply to work performed under this test plan.

5.5 Data Integrity

Care will be taken while conducting these test activities to ensure the integrity of all data collected including documentation on hard copy and electronic data collected on storage media. Duplicate copies of all data will be produced as quickly as possible and the duplicate copies will be maintained at a location separate from the test site to ensure that data are not lost.

5.6 Records

Records will be maintained as described in this test plan and applicable FCT QA implementing procedures. These records may consist of bound scientific notebook(s), loose-leaf pages, forms, printouts, or information stored on electronic storage media. The test principal investigator or designee will ensure that the required records are maintained and submitted to the designated records archive location.

5.6.1 Required QA Records

As a minimum, QA records will include:

- Data forms in association with activity specific procedures;
- All forms containing manually-collected data;
- Calibration records for all controlled equipment;
- Equipment-specification sheets or information (if available);
- Scientific notebook(s);
- Standard sample description and handling forms, fully completed (if used)
- Chain-of-custody forms (if physical samples are collected)

5.6.2 Miscellaneous Non-QA Records

Additional records that are useful in documenting the history of the activities, but are considered non-QA records, may be maintained and submitted to the Records Center. These records include:

- Personal log books of daily activities
- safety briefings;
- Environmental Safety and Health (ES&H) documentation;
- as-built diagrams of equipment; and
- equipment manuals and specifications;

These records do not support regulatory compliance and, therefore, are not quality-affecting information.

5.6.3 Submittal of Records

QA records generated through the implementation of this test plan shall be prepared and submitted to the SNL FCT Quality Assurance SharePoint site and submitted to EIMS in accordance with the SNL Records Management Manual and IM 100.2.2 Control of Records (Manage and Protect Information).

6.0 TRAINING

All personnel involved in the experiments described in this test plan will be trained and qualified for their assigned work. This requirement will be implemented through procedure FCT QAP 2-1 *Qualification and Training*. In addition, personnel should read the facility specific environmental, safety, and health (ES&H) procedure for working underground. Any personnel working underground should either have current training credentials or be escorted by someone who does.

Activity/procedure specific training along with procedures will be provided for installing and operating the extensometer systems and fluid flow systems. This training will cover emergency shut-down of equipment.

7.0 HEALTH AND SAFETY

All of the health and safety requirements relevant to the underground work described in this test plan will be described in facility specific (ES&H) standard operating procedures for working underground. This procedure will describe the non-radiological hazards associated with these experiments and describes the procedures to deal with those hazards, including all the training requirements for personnel involved in conducting the experiments. Activity specific procedures will have a section devoted to operations safety where appropriate. Additional procedures may be mandated by various organization ES&H requirements and their issuance will not require revision of this test plan.

The fluid flow test equipment will used compressed gas (nitrogen) and will contain sufficient stored energy to be classified as a pressure system. These systems will require that a pressure safety data package be prepared.

8.0 PERMITTING/LICENSING

An evaluation will need to be made to determine if any special licenses or permits will be needed for the work described in this test plan. No hazardous materials are planned to be used. The injection of gas or brine in the fluid flow tests will be on the order of 10s of milliliters and is expected to be permissible under operating permits associated with the test facility. The permitting evaluation will be facilitated by interactions with the underground facility managing and operating contractor during the planning phase. These interactions will be conducted following standard facility conduct-of-operations procedures.

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APPENDIX A

Technical Background Related to Salt Mechanical Deformation and Test Methods

Characterizing a Generic Test Bed in a Geologic Salt Formation

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Introduction

In-situ tests implemented in an underground facility mined from salt deposits, if planned appropriately, provide an opportunity to characterize the host rock before, during, and after excavation of test rooms. For example, an operational demonstration of in-drift emplacement of Department of Energy (DOE) defense waste canisters could be conducted in two parallel drifts and the host rock containing these drifts could be instrumented ahead of time to measure mechanical changes as a result of mining. Characterization of the test bed[1] is essential to interpret structural deformation including formation and evolution of the disturbed rock zone (DRZ). Characterization also includes measurement of first-order effects on the poroelastic evolution of the salt from an impermeable undisturbed state to a more-transmissive DRZ. This preliminary overview of a potential Test Plan enumerates recommended geophysical measurements that fundamentally characterize the initial state of the test bed and its evolution over the course of an underground 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 (DQOs) to characterize the test bed in an underground salt research facility.

A Test Plan to be written for this proposed work would conform to the appropriate planning procedure under the provisions of the sponsoring program's quality assurance requirements. Requirements, specifications, and data management would also be included in the Test Plan and implementing procedures. The Test Plan should contain sufficient detail to install gauges, conduct tests, and describe applicable functional and test-specific requirements. When approved, the Test Plan provides the primary means to reach a documented consensus on all aspects of a test or experiment, including design, cost, schedule, interface controls, and data management. Test Plans allow review and documentation of the test effort and they serve as an agreement between the Principal Investigator, the test implementing organization, and the authorizing management.

The most important measurements to be made will describe the evolutionary geomechanical and poroelastic characteristics of the test bed, focusing on providing boundary conditions for a generic drift-scale ambient-temperature or heated test. Potential secondary measurements will be considered in the Test Plan to better characterize site environmental conditions if they would be desired by other Principal Investigators. In addition to generally establishing in situ conditions of an underground research facility, the Test Plan would define a measurement scheme to establish boundary conditions for any in-drift testing.

Mechanical deformation of the rock in a salt formation surrounding excavations controls the development of "initial conditions" resulting from excavating the drift, which affect any later tests in these drifts. Total geomechanical deformation comprises instantaneous elastic deformation, salt creep

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[1] "test bed" is a term that means the physical space where the underground test is to be performed. In this document, it would mean the space within and immediately surrounding the test rooms, where testing hardware (heaters, thermocouples, extensometers, and hydrology packers, for example) would be placed.

(governed by crystal plasticity) and damage imparted to the host rock under certain stress conditions. Combined, these processes can be quantified through observations of deformation rates, finite displacements, and poroelastic characteristics of the DRZ. A drift-scale heated test could involve modest heat input in test drifts. Measurements of temperature change in the host rock surrounding the test drifts would confirm our understanding of thermal conductivity of the salt formation.

Geomechanical Measurements

Testing techniques proposed here have previously been implemented in underground openings in geologic salt deposits, are mostly generic in nature, and will be described as situated in and around a typical underground drift configuration appropriate to geologic waste disposal. Evaluation of in situ conditions and evolution of the underground will add to our understanding of geomechanical processes in salt.

Testing and monitoring include

- Formation deformation and strain rate
- Temperature
- Brine and gas flow in deforming media
- Barometric pressure and humidity in-drift and its associated DRZ

Plastic flow of salt (i.e., creep) has been extensively measured and characterized by U.S. and German salt repository programs and other salt-based industries (e.g., salt and potash mining). Crystal plasticity is isochoric; therefore, it does not induce damage to the salt matrix. Damage occurs when the deviatoric (i.e., shear) stresses are relatively high compared to the applied mean stress. 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. Geomechanical modeling can account for and predict the microfracturing process, estimating damage the rock will experience. The extent of the DRZ surrounding mined openings has been measured directly at the Waste Isolation Pilot Plant (WIPP) and elsewhere using techniques such as sonic velocity, brine and gas flow behavior, and laboratory analysis of cores. Point geophysical measurements have validated the geometry and rock properties predicted by numerical damage models. These features and their measurements are discussed subsequently.

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, which are described in detail in Hansen (2003) and Hansen and Leigh (2011). Observed room closure is a result of several concurrent geomechanical processes, including elastic deformation, plastic creep, decoupling along thin clay layers, damage, and shear.

A structural model prediction of the state of the test drifts will be run to provide guidance for instrumentation placement. This calculation needs to be based on a salt-creep constitutive model that tracks stress/strain history of the host rock. Examples of how such calculations would inform testing and monitoring are given in subsequent DRZ discussions. The expected results from the structural calculation can be supplemented and corroborated by taking advantage of extensive database of geotechnical measurements made in connection with underground operations in salt. Data from WIPP Panel 1 entry, as shown in Figure 1, is an example of existing data recorded in association with salt deformation of an excavation. Panel closure rates are driven by the magnitude of lithostatic stresses and excavation size and geometry.

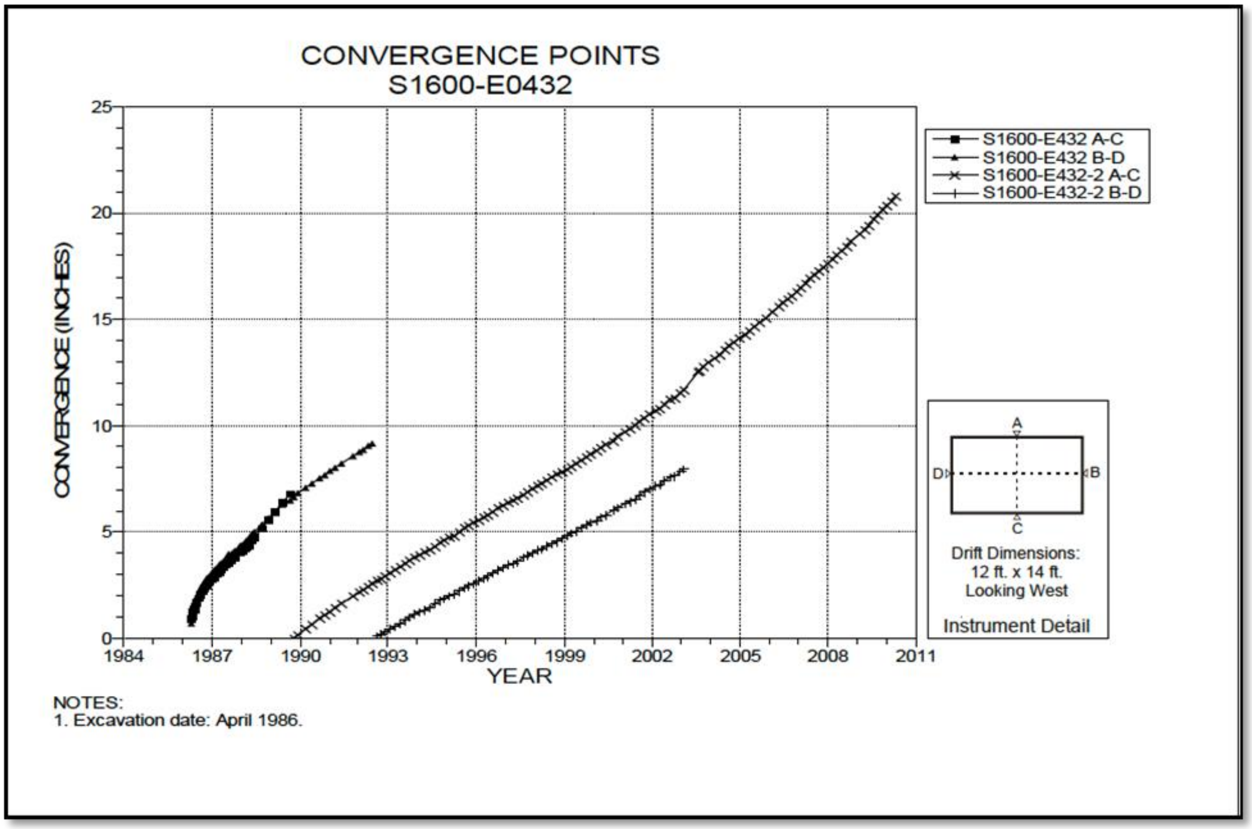

Figure 1. Excavation closure measurements in a salt formation

Transient deformation in excavations is initially rapid and slows to a pseudo steady-state as substructure evolves with time. Figure 1 does not fully account for expected closure behavior because it does not capture the early transient behavior. Model simulations can be used to provide a more complete deformation history, including hard-to-collect very early-time data. In addition, the extent of damage around the excavation of Figure 1 is not reflected in these convergence measurements. Model predictions include continuous predictions of DRZ extent and absolute displacement quantities. Geomechanical model predictions provide the basis for instrumentation range, accuracy, and DQOs, which quantify needed measurement precision and accuracy based on measurement application.

Damage Evolution

Laboratory and field studies of salt damage are summarized by Hansen and Leigh (2011). Van Sambeek et al. (1993) reexamined the extensive creep data collected during years of experiments on salt, they evaluated volumetric strain in terms of principal stresses (Figure 2). Stress states that led to damage and 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 stress, respectively, and are defined as follows:

$$I_1 = 3\sigma_m = \sigma_1 + \sigma_2 + \sigma_3$$

$$J_2^{1/2} = \left\{\frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]\right\}^{1/2}$$

where σ_m is the mean stress and σ_1, σ_2, and σ_3 are the three principal stress components Using these definitions, Van Sambeek et al. (1993) demonstrated that 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. They suggested an empirical relationship to divide dilating stress states from nondilating stress states and expressed this relationship as

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

This relationship is called the stress-invariant model and has been used for several applications in analyses of drift geotechnical barriers and shaft seal systems.

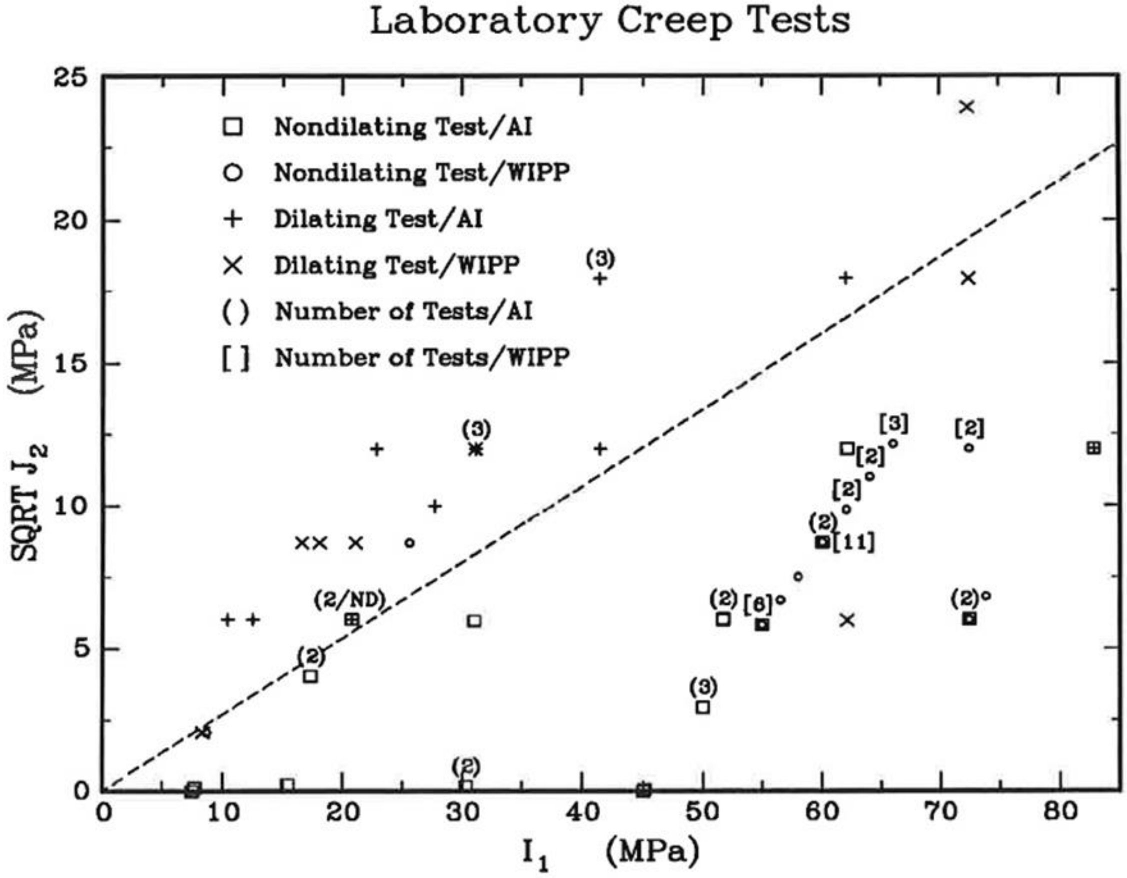

Figure 2. Laboratory data delineating damage and isochoric stress space from Van Sambeek et al. (1993).

Actual measurements of the DRZ in the underground have been made using various geophysical techniques, which are also summarized by Hansen and Leigh (2011). Predictions of the one-way evolution of the DRZ (without subsequent long-term salt healing) replicate underground observations.

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 from microscopy of core damage (Hansen, 2003).

Damage Calculations

The stress-invariant criterion has been widely applied and provides a tool for pre-test calculations of the test room conditions. An example damage calculation is given in Figure 3. Here the zone shown in black is clearly damaged with a *Damage Factor* > 1. Damage in the adjacent gray zone is less clear because that volume of rock is calculated to have undergone a stress/strain history that approaches threshold conditions observed to cause damage in laboratory tests. This type of model prediction should be run for any test configuration such that the periphery of the damage zone can be approximated from model output. Multipoint Borehole Extensometers (MPBX) could be situated to straddle the predicted extent of the DRZ and provide confirmation of its evolution. We would also situate permeability testing boreholes in the expected DRZ. This combination of strain and fluid testing will generate data to allow a correlation to be made between a 1-D stain level and a fluid flow potential.

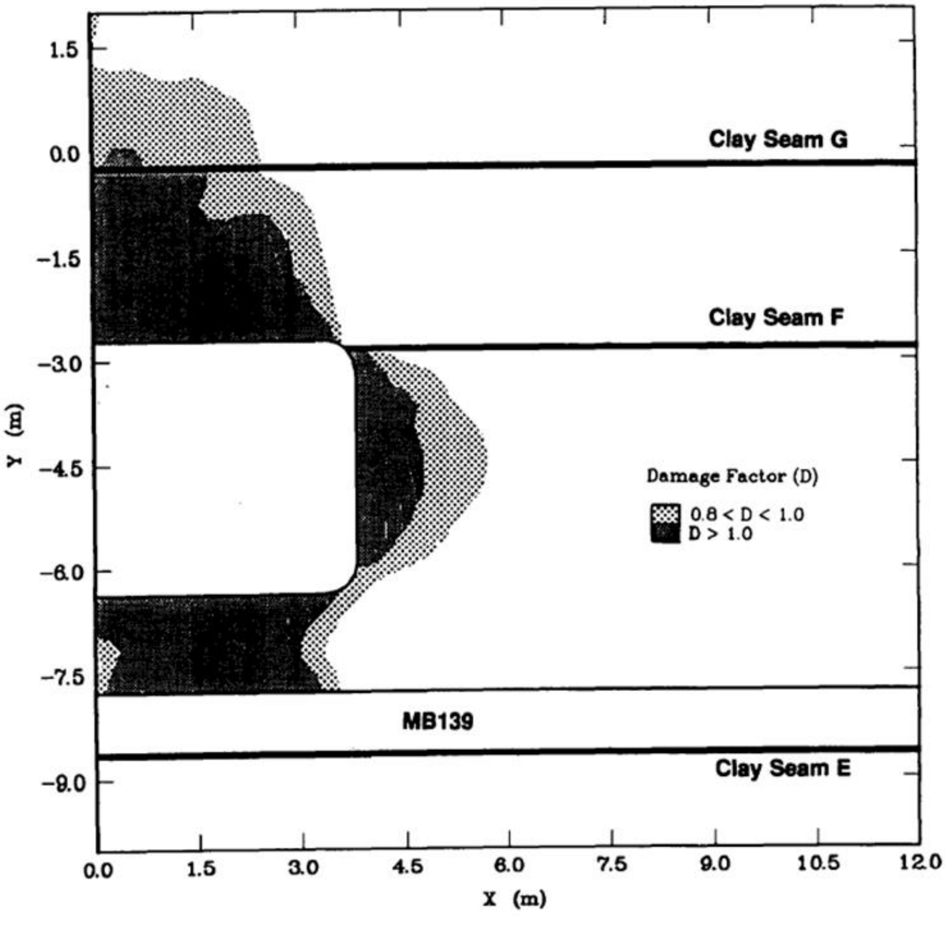

Figure 3. Damage zone calculated around a rectangular room at WIPP in a 40 year-old room (Van Sambeek et al., 1993).

The Sandia SIERRA Mechanics code suite supplies the basic building blocks for realizing a multiphysics capability for repository systems engineering. These simulation tools provide an adaptive multiphysics framework for addressing the disparate time and length scales associated with geomechanics problems such as waste disposal. Discriminating features of this highly nonlinear, thermal-mechanical analysis include the use of large-strain, large-deformation mechanics and the use of both thermal and mechanical contact surfaces. Although the example above is isothermal, two-dimensional, and assumes plane strain, the SIERRA Mechanics tools can readily provide fully-coupled, three-dimensional, massively-parallel, thermal-mechanical analysis of a generic salt repository for heat generating waste in order to guide future testing and experimentation.

Deformation Instrumentation

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 (the access drifts are parallel and perpendicular to the testing drifts and 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 significant early transient deformation. After the drifts are excavated, symmetric instrumentation will be placed from within each drift before additional in-drift test hardware or materials (e.g., heaters or related in-drift instrumentation) are brought to the drift 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 homologous locations to enable data collection for thermal-expansion compensation of the extensometers. Final Test Plan design depths, ranges, and DQOs would be aided by final testing site selection and preliminary geomechanical model predictions.

Brine and Gas Flow through Damaged Salt

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%) and it is filled with saturated brine. Pore pressure is difficult to measure in an undisturbed state due to the very low permeability, but it is driven largely by 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 (Beauheim and Roberts, 2002).

Beginning immediately after 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, allowing 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 towards the excavation were explored numerically for the WIPP Room Q brine inflow experiment (Freeze et al., 1997). These modeling results corroborated that mechanical effects (increase in porosity and permeability due to damage) control and drive the hydrologic system, and must be characterized to properly understand the initial state of 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 (closing fracture apertures associated with accumulated damage to the core from extraction and handling – permeability decreases during this period), which does not occur during field observations, such as those shown in Figure 5. 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 happen quickly (within weeks or months), while stage III occurs over longer periods. The Stage III damage behaviors in the field are manifest after years in WIPP excavations.

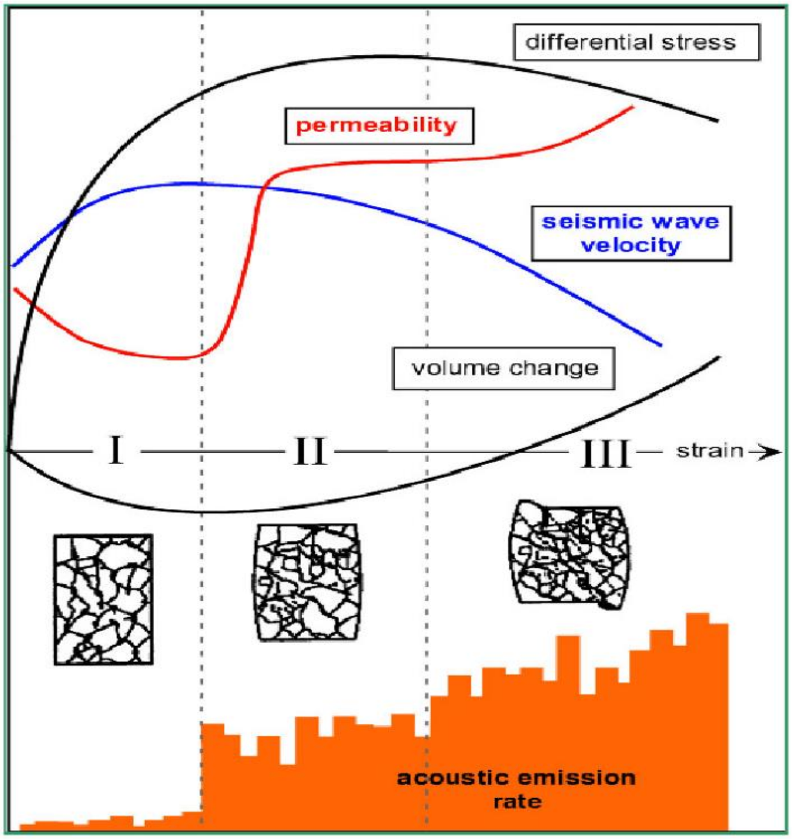

Figure 4. Physical property changes in salt during typical salt core deformation in laboratory testing (Schulze et al., 2001).

Once the changes to the porosity, intrinsic permeability, and brine saturation have occurred, brine flows into the DRZ under the influence of the driving forces of gravity, pressure, and capillarity. This redistribution of brine is much 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 exists from 1-2 meters up to one excavation “radius” into the host rock, and is important to characterize for two reasons. First, this provides concrete information regarding the initial and boundary conditions in an in situ test drift, as the

DRZ can act as a source, sink, and pathway for brine and vapor moisture before and during conduct of an underground test. Secondly, characterizing the spatial extent and temporal evolution of the DRZ around excavations provides an important boundary condition for any of the proposed experiments.

Gas Flow

Laboratory and in situ testing programs at WIPP have characterized both brine and gas flow through the DRZ (e.g., Beauhiem and Roberts, 2002; Stormont, 1997). In general, gas flow measurements are simpler to conduct in areas where the air entry pressure is low enough (i.e., the DRZ), and make a good tool for delineating the extent of the DRZ (see Figure 5). Estimates of DRZ extent and shape from gas flow measurements are qualitatively similar to those estimated from geomechanical model predictions and cross-hole sonic velocity measurements. Gas flow rate can be measured at a specified working pressure, into a short packed-off borehole interval. The test is relatively quick to conduct, and can be repeated across different intervals in the boreholes 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 the absence of a DRZ due to the construction of the access drifts, and to confirm the creation of the DRZ upon test room mining.

Gas is a non-wetting fluid, and would only displace brine (the wetting fluid) under relatively high pressures when intergranular porosity had pore diameters that allowed such displacement. 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 DRZ damage extent – similar to that shown in Figure 5. Very high gas flow rates are associated with macroscopic fractures and bedding separations, often associated with the non-salt components, which can be comprised of relatively brittle materials.

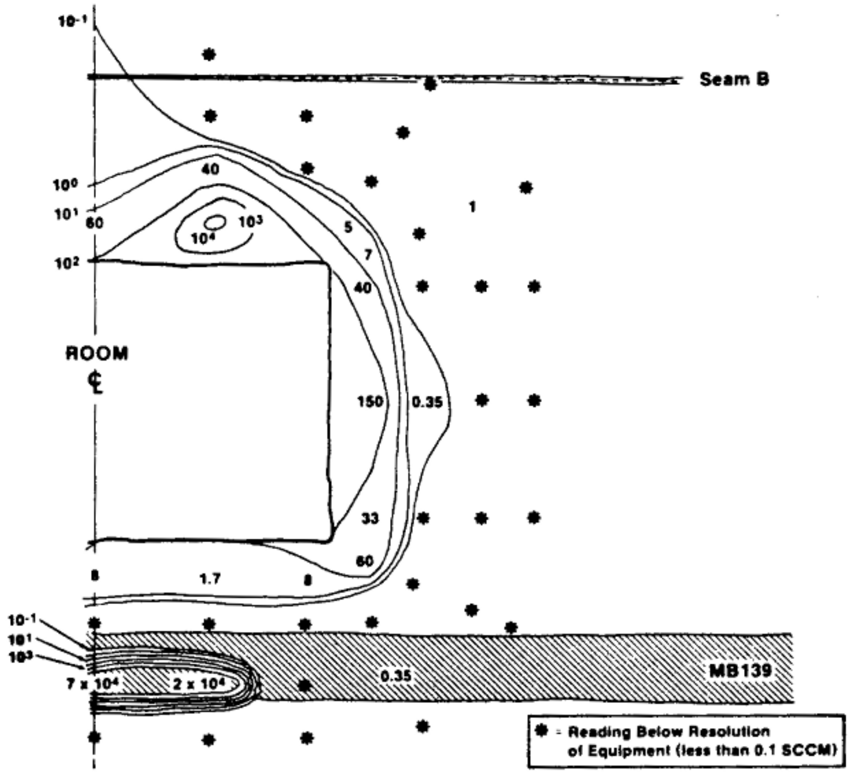

Figure 5. DRZ Gas flowrate contours. (Borns and Stormont, 1988).

We propose to make gas and brine flow measurements from boreholes originating in access drifts (rather than in the test drift) for two reasons. First, this allows the DRZ and permeability testing to be performed before, during, and after mining to characterize the evolution of the boundary conditions for the test bed. Secondly, this arrangement unclutters the test drift by getting some of the test equipment out of the test drifts, which may have a large amount of instrumentation associated with tests or demonstrations within the excavations.

Brine Flow

Brine Flow in Packed-off Boreholes

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 (Roberts et al., 1999). 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. Brine permeability measurements beyond the DRZ are difficult to make due to the very low permeability of intact salt. 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 penetrating significant gas-filled 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 a very 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.

Brine Flow in Open Boreholes

Interbeds comprised of non-creeping minerals typically exist within salt formations. In excavations similar to that proposed for the this test configuration, such interbeds become highly fractured due to the extent of the DRZ and the brittle behavior of the interbeds. Figure 5 illustrates high gas flow rates observed in Marker Bed 139 (MB139) by Borns and Stormont (1988) in the N1100 drift at WIPP during testing in the 1980s. The Brine Sampling and Evaluation Program (BSEP) conducted at WIPP from 1982 to 1993 included brine “water table” observations in MB139 using some vertical boreholes (Deal et al., 1995; Appendix E). They found brine readily flowed into boreholes completed in the marker bed, especially at the intersection of large drifts. In this test planning exercise, two boreholes are to be completed to the bottom of an interbed located below the test excavations near both ends of each of the test drifts (in logistically convenient locations) before mining of the test drifts (both up-dip and down-dip of the test room). Brine accumulation level will be monitored in these boreholes using either a tape measure or a pressure gage located at the bottom of the holes. Short pumping or purging tests may be conducted to estimate permeability of the damaged zone penetrated by these boreholes.

Based on prior experience, a relatively brittle stratum located beneath an excavation will potentially act as a brine collection drain for the test drifts because of its stratigraphic location (Kuhlman and Malama, 2014). Since these are simple measurements, they are worth performing to understand and potentially quantify brine flow through interbed fracture networks, at the scale of the rooms and pillars associated with the test drifts, which is an important boundary condition for any in-drift measurements.

Relative Humidity and Barometric Pressure

A heated room test concept will need to be designed recognizing that water vapor transports heat and moisture though the DRZ, room bulkheads, and any backfill used in the test. Moisture in the form of brine is anticipated to be driven into near-field host rock by a combination of formation pore pressure, capillarity, and gravity forces. In the increased-porosity DRZ, brine movement through the DRZ will occur as multi-phase two-component unsaturated flow (air and vapor being much more mobile than brine). As vapor, water will be available for movement into and through the test drift and any backfill. Relative humidity and barometric pressure associated with the near-field and in-room conditions, which may affect moisture transport, should be measured in the drift and into the DRZ and host rock.

Substantial moisture could migrate from a heated test room through the room bulkheads and DRZ. This includes liquid water flowing through fractures in interbeds that result from stress redistribution into this relatively brittle stratum. A bedded geologic deposit will typically dip, creating a gravity driven gradient. Stratigraphic discontinuities such as anhydrite, when located beneath excavations, can be associated with noticeable quantities of brine originating in clay layers, but also because it is a natural gravity-fed sump for the room DRZ.

Moisture in the vapor phase moves both by diffusion and pressure gradients. Moisture gradients can be created by heated room bulkheads if present, which will limit atmospheric gas movement into and out of the room. Completely sealed drifts are expected to have a relative humidity around 75%, which is the vapor pressure over salt saturated solutions, while the ventilation air is typically much less. But most bulkheads will not be truly “sealed” and vapor will move around them through the DRZ (Jensen et al., 1993). Pressure gradients are established by fluctuations in atmospheric pressure and pressure-loss as ventilation air moves through the access drifts from one side of the test rooms to the other. Thus the up-stream side of the test rooms will necessarily be at higher air pressure than the down-stream side.

A suite of gauges and observations could be used to quantify some of the atmospheric gradients and flow. Relative humidity (RH) and barometric pressure could be measured both inside and outside the test rooms, in boreholes completed to the DRZ and in the open air. Gauges and pressure tubes inside the room could be located in boreholes penetrating pillars to allow gauge maintenance without having to enter the room.

Barometric pressure and relative humidity could be measured in DRZ gas-flow testing boreholes to quantify connection of the DRZ to the test room air. The humidity data could quantify whether the air in the DRZ is in equilibrium with the salt and brine (~75% RH). Analysis of the barometric pressure time series in the drifts and DRZ boreholes may also provide further estimates of DRZ gas permeability by virtue of observed lag in barometric pressure fluctuations. These observations could be used to make a differential pressure reading across the DRZ to estimate its gas-flow properties.

Data Quality Objectives

A quality scientific endeavor is predicated on sound application of the scientific method. This document provides a look forward to a Test Plan for conduct in a geologic salt deposit and will describe measurements in the undisturbed state and as physical characteristics change during and after excavation. Because of extensive history in this type of experimental work, both in the U.S. and internationally, the basic material and geologic formation behavior is well known. We therefore have an opportunity to confirm our understanding of these physical changes, while providing detailed boundary conditions for underground experiments. In addition, results of these measurements provide opportunities for validation of modeling techniques.

The author has extensive personal experience in measuring properties of salt. Undamaged salt is essentially impermeable, while minimal damage (volumetric strains as small as 0.01%) will increase anisotropic permeability by 5-6 orders of magnitude (Figure 5). Reversing the stress state toward equilibrium and simultaneously reducing shear stress will heal salt fractures. Understanding these two processes of creating and healing the salt DRZ has been sufficient for engineering and seal system applications to date. Geomechanical simulations can track the stress state and post-process the ratios of invariants (Figure 2 for example) for the damage contours.

In the 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 in this document. Pending structural modeling outcome, preliminary DQOs for the Test Plan are provided below:

- **Extensometers**: +/- 0.01 strain or 1 mm. As noted in the text and from underground measurements in rooms analogous to the proposed test drifts, roof-to-floor closure on the order of 100 mm could be expected. Within the rock mass, the 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**: +/- 1^{o} C. Variability within 1^{o} C is well within expected modeling accuracy and natural variability.
- **Pore pressure**: ~10% of measured value. The pore pressure resolution of 10% is for three reasons:

  1) pore pressures vary spatially naturally. This variation can be ~10% for the scale of measurements proposed in this test,

  2) The pore pressure provides a boundary condition for modeling flow tests where permeability is estimated to the nearest order of magnitude.

  3) Experience has shown that 10% uncertainty in pore pressure is sufficient for modeling field test data.
- **Brine flow in host rock**: ~1 cc/day. Small-scale mine-by testing (around a 1 m diameter borehole) performed previously showed that a flow of 1 cc/day using a constant pressure test configuration corresponded in that geometry to about 10^{-20} 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^{-20} m^2 or more can be expected if the rock mass has been mechanically disturbed.
- **Gas flow**: threshold only (flow or no-flow) at low working pressure
- **Relative Humidity**: ~10% of measured value, with relative humidity accuracy between gages (differential humidity between drift air and DRZ boreholes) being more important than absolute humidity accuracy.
- **Barometric-ventilation pressure**: 0.001 psi, with relative pressure accuracy between gages (differential pressure between drift air and DRZ boreholes) being more important than absolute pressure accuracy.
- Scan frequencies of up to 1 Hz may be needed for some transient tests and during excavation of test rooms (during the mine-by).

Concluding Remarks

This document describes modeling, testing, and measurement methods that can be used to characterize a generic test bed that could be created in an underground geologic salt formation. An actionable Test Plan to proceed with the described scope of work would conform to requirements of the sponsoring agency under the provisions of an appropriate quality assurance plan. In this preview, a variety of fundamental phenomena and appropriate means to collect relevant information has been presented.

Underground investigations and salt characterization, as described here, would not only characterize the a particular test bed, they would be of great interest to the international salt repository community.

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Appendix B

Borehole Layout

Extensometer Borehole Identification and Layout Information

Centroid of measurements is shifted 0 east of pillar mid-point

Reference for Test Drift Holes is a point located in the theoretical center of the room. (X is N-S, Y is E-W, Z is up and down)

Reference for access drift holes is a point located 5 feet off the floor at room mid-point - Room is assumed to be 16' wide (X is N-S, Y is E-W)

N, E, and up are positive directions.

Room - Test Drift 1 (Northern Room)

Borehole ID Number	Collar Location				Orientation		Depth (ft)	Diameter (in)	Purpose	comment
	Room	X (ft)	Y (ft)	Z (ft)	Azimuth (deg from N)	Inclination (+/-degrees)				
TD1-20.0-MPX-01	North Access	-8	0	0	180	0.0	34.3	4	4-point Ext	horizontal - hole bottom 6" from room
TD1-20.0-MPX-02	Test Drift 1	0	0	5	n/a	90	40.0	4	4-point Ext	Vertical up into back
TD1-20.0-MPX-03	Test Drift 1	-8	0	0	180	0	17.4	4	4-point Ext	Horizontal - into mid-pillar
TD1-20.0-MPX-04	Test Drift 1	0	0	-5	n/a	-90	40.0	4	4-point Ext	Vertical down into invert

Room - Test Drift 2 (Southern Room)

Borehole ID Number	Collar Location				Orientation		Depth (ft)	Diameter (in)	Purpose	comment
	Room	X (ft)	Y (ft)	Z (ft)	Azimuth (deg from N)	Inclination (+/-degrees)				
TD2-20.0-MPX-01	Test Drift 2	8	0	0	0	0	17.4	4	4-point Ext	Horizontal - into mid-pillar
TD2-20.0-MPX-02	Test Drift 2	0	0	5	n/a	90	40.0	4	4-point Ext	Vertical up into back
TD2-20.0-MPX-03	South Access	8	0	0	0	0.0	34.3	4	4-point Ext	horizontal - hole bottom 6" from room
TD2-20.0-MPX-04	Test Drift 2	0	0	-5	n/a	-90	40.0	4	4-point Ext	Vertical down into invert

Fluid Flow Borehole Identification and Layout Information

Centroid of measurements is shifted 5 east of pillar mid-point

Reference for Test Drift Holes is a point located in the theoretical center of the room. (x is N-S, Y is E-W)

Reference for access drift holes is a point located 5 feet off the floor at room mid-point - Room is assumed to be 16' wide (x is N-S, Y is E-W)

N and E are positive directions.

Room - Test Drift 1 (Northern Room)										
Borehole ID Number	Collar Location				Orientation		Depth (ft)	Diameter (in)	Purpose	comment
	Room	X (ft)	Y (ft)	Z (ft)	Azimuth (deg from N)	Inclination (+/-degrees)				
TD1-25.0-FFB-01	North Access	-8	5	0.5	180	-1.0	33.76	2	Fluid Flow Brine	mid height in rib - hole bottom is 15" from rib
TD1-25.0-FFB-02	North Access	-8	5	3	180	5.23	43.91	2	Fluid Flow Gas	24" above back
TD1-25.0-FFB-03	North Access	-8	5	-3	180	-5.21	43.94	2	Fluid Flow Brine	24" below invert
TD1-25.0-FFB-04	North Access	-8	2	-3	180	-5.21	43.94	2	Fluid Flow Gas	24" below invert
TD1-25.0-FFB-05	West Access/ref=TD1	-10.5	-40	0.80	88.75	-1.0	45.75	2	Fluid Flow Brine	~parallel to room 18" in rib
TD1-25.0-FFB-06	West Access/ref=TD1	-11.58	-40	-3	76	-13.89	49.11	2	Fluid Flow Gas	Through MB139

Room - Test Drift 2 (Southern Room)										
Borehole ID Number	Collar Location				Orientation		Depth (ft)	Diameter (in)	Purpose	comment
	Room	X (ft)	Y (ft)	Z (ft)	Azimuth (deg from N)	Inclination (+/-degrees)				
TD2-25.0-FFB-01	South Access	8	5	0.5	0	-1.0	33.76	2	Fluid Flow Gas	mid height in rib - hole bottom is 15" from rib
TD2-25.0-FFB-02	South Access	8	5	3	0	5.23	43.91	2	Fluid Flow Brine	24" above back
TD2-25.0-FFB-03	South Access	8	5	-3	0	-5.21	43.94	2	Fluid Flow Gas	24" below invert
TD2-25.0-FFB-04	South Access	8	2	-3	0	-5.21	43.94	2	Fluid Flow Brine	24" below invert
TD2-25.0-FFB-05	West Access/ref=TD2	10.5	-40	0.80	91.25	-1.0	45.75	2	Fluid Flow Gas	~parallel to room 18" in rib
TD2-25.0-FFB-06	West Access/ref=TD2	11.58	-40	-3	104	-13.89	49.11	2	Fluid Flow Brine	Through MB139

Appendix C

Gage Identification and Layout

Extensometer Gage Identification and Location Information

Borehole Number	Room	Gage Number	Anchor Depth from collar rib (ft)
TD1-20.0-MPX-01	North Access	TD1-20.0-MPX-01-1	34.3
		TD1-20.0-MPX-01-2	31.4
		TD1-20.0-MPX-01-3	24.8
		TD1-20.0-MPX-01-4	17.4
TD1-20.0-MPX-02	Test Drift 1	TD1-20.0-MPX-02-1	40
		TD1-20.0-MPX-02-2	20
		TD1-20.0-MPX-02-3	10
		TD1-20.0-MPX-02-4	4
TD1-20.0-MPX-03	Test Drift 1	TD1-20.0-MPX-03-1	17.4
		TD1-20.0-MPX-03-2	10
		TD1-20.0-MPX-03-3	6
		TD1-20.0-MPX-03-4	3
TD1-20.0-MPX-04	Test Drift 1	TD1-20.0-MPX-04-1	40
		TD1-20.0-MPX-04-2	20
		TD1-20.0-MPX-04-3	10
		TD1-20.0-MPX-04-4	4
TD1-20.0-MPX-01	Test Drift 2	TD1-20.0-MPX-01-1	17.4
		TD1-20.0-MPX-01-2	10
		TD1-20.0-MPX-01-3	6
		TD1-20.0-MPX-01-4	3
TD1-20.0-MPX-02	Test Drift 2	TD1-20.0-MPX-02-1	40
		TD1-20.0-MPX-02-2	20
		TD1-20.0-MPX-02-3	10
		TD1-20.0-MPX-02-4	4
TD1-20.0-MPX-03	South Access	TD1-20.0-MPX-03-1	34.3
		TD1-20.0-MPX-03-2	31.4
		TD1-20.0-MPX-03-3	24.8
		TD1-20.0-MPX-03-4	17.4
TD1-20.0-MPX-04	Test Drift 2	TD1-20.0-MPX-04-1	40
		TD1-20.0-MPX-04-2	20
		TD1-20.0-MPX-04-3	10
		TD1-20.0-MPX-04-4	4

Fluid Flow Gage Identification Information

Hole Number	Room Number	Gage Number	Comment
TD1-25.0-FFB-01	North Access	TD1-25.0-FFB-01-1	Test Interval Pressure
		TD1-25.0-FFB-01-2	Packer Pressure
TD1-25.0-FFB-02	North Access	TD1-25.0-FFB-02-1	Test Interval Pressure
		TD1-25.0-FFB-02-2	Packer Pressure
TD1-25.0-FFB-03	North Access	TD1-25.0-FFB-03-1	Test Interval Pressure
		TD1-25.0-FFB-03-2	Packer Pressure
TD1-25.0-FFB-04	North Access	TD1-25.0-FFB-04-1	Test Interval Pressure
		TD1-25.0-FFB-04-2	Packer Pressure
TD1-25.0-FFB-05	West Access/ref=TD1	TD1-25.0-FFB-05-1	Test Interval Pressure
		TD1-25.0-FFB-05-2	Packer Pressure
TD1-25.0-FFB-06	West Access/ref=TD1	TD1-25.0-FFB-06-1	Test Interval Pressure
		TD1-25.0-FFB-06-2	Packer Pressure
TD1-25.0-FFB-01	South Access	TD1-25.0-FFB-01-1	Test Interval Pressure
		TD1-25.0-FFB-01-2	Packer Pressure
TD1-25.0-FFB-02	South Access	TD1-25.0-FFB-02-1	Test Interval Pressure
		TD1-25.0-FFB-02-2	Packer Pressure
TD1-25.0-FFB-03	South Access	TD1-25.0-FFB-03-1	Test Interval Pressure
		TD1-25.0-FFB-03-2	Packer Pressure
TD1-25.0-FFB-04	South Access	TD1-25.0-FFB-04-1	Test Interval Pressure
		TD1-25.0-FFB-04-2	Packer Pressure
TD1-25.0-FFB-05	West Access/ref=TD1	TD1-25.0-FFB-05-1	Test Interval Pressure
		TD1-25.0-FFB-05-2	Packer Pressure
TD1-25.0-FFB-06	West Access/ref=TD1	TD1-25.0-FFB-06-1	Test Interval Pressure
		TD1-25.0-FFB-06-2	Packer Pressure

Barometric Pressure Gage Identification Information

Gage Number	Location
TD1-XX.X-HYD-01-1	Test Drift 1
TD1-XX.X-HYD-02-1	Test Drift 2
EAD-XX.X-HYD-03-1	East Access Drift
WAD-XX.X-HYD-04-1	West Access Drift

Appendix D

Geomechanical Modeling of Test Drifts

Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico 87185

Date: September 12, 2014

To: Kristopher Kuhlman, 06224 and Frank D. Hansen, 06910

From: John F. Holland, 1526

Subject: Structural Analysis of a Proposed Mine-by Test in Salt

Summary

A preliminary two-dimensional isothermal structural analysis of a proposed mine-by test (as part of a larger underground research laboratory) in salt has been performed. The primary reason for the calculation is to determine the extent of the damage zone around Test Drift 1 (TD1), and to aid in the design and placement of instrumentation. If such an excavation is actually made at some future date, we would have an additional opportunity to validate these calculations.

Finite Element Model

The finite element model of the underground openings represents a two-dimensional cross-section passing through the mid-length of a nominal test drift. The two-dimensional geometry was chosen, because the analysis was time and budget limited. To more accurately model the mine-by experiment a full three-dimensional model is required. The mesh consists of 13,937 hexagonal elements. Figure 1 shows a mesh detail around access drift N-940 and drift TD1. Figure 2 shows a plan view of the proposed mine-by test drifts with access drifts. The material layering used in the model is based upon WIPP Room D stratigraphy (see Figure 3), which can be considered typical for bedded salt. The model is restrained against normal displacement on the vertical planes and on the horizontal plane at the bottom of the model. On the top horizontal plane a pressure of 13.57×10^6 Pa is applied that is equal to the overburden. Figures 3 and 4 shows the outline of the model and illustrate its' boundary conditions. Sandia's implicit finite element code Adagio (part of the SIERRA Mechanics framework) was used to simulate isothermal mechanical deformation.

A final test location with site geology and mining sequences should be used to develop a three-dimensional geo-mechanical model of the area, especially since the purpose of the mine-by experiment is to quantify the damage of the salt and the development of the disturbed rock zone surrounding test drifts which may be used for heated tests or other purposes. Testing measurements will quantify the evolution of the underground setting and include strain, strain rate, displacement, and permeability.

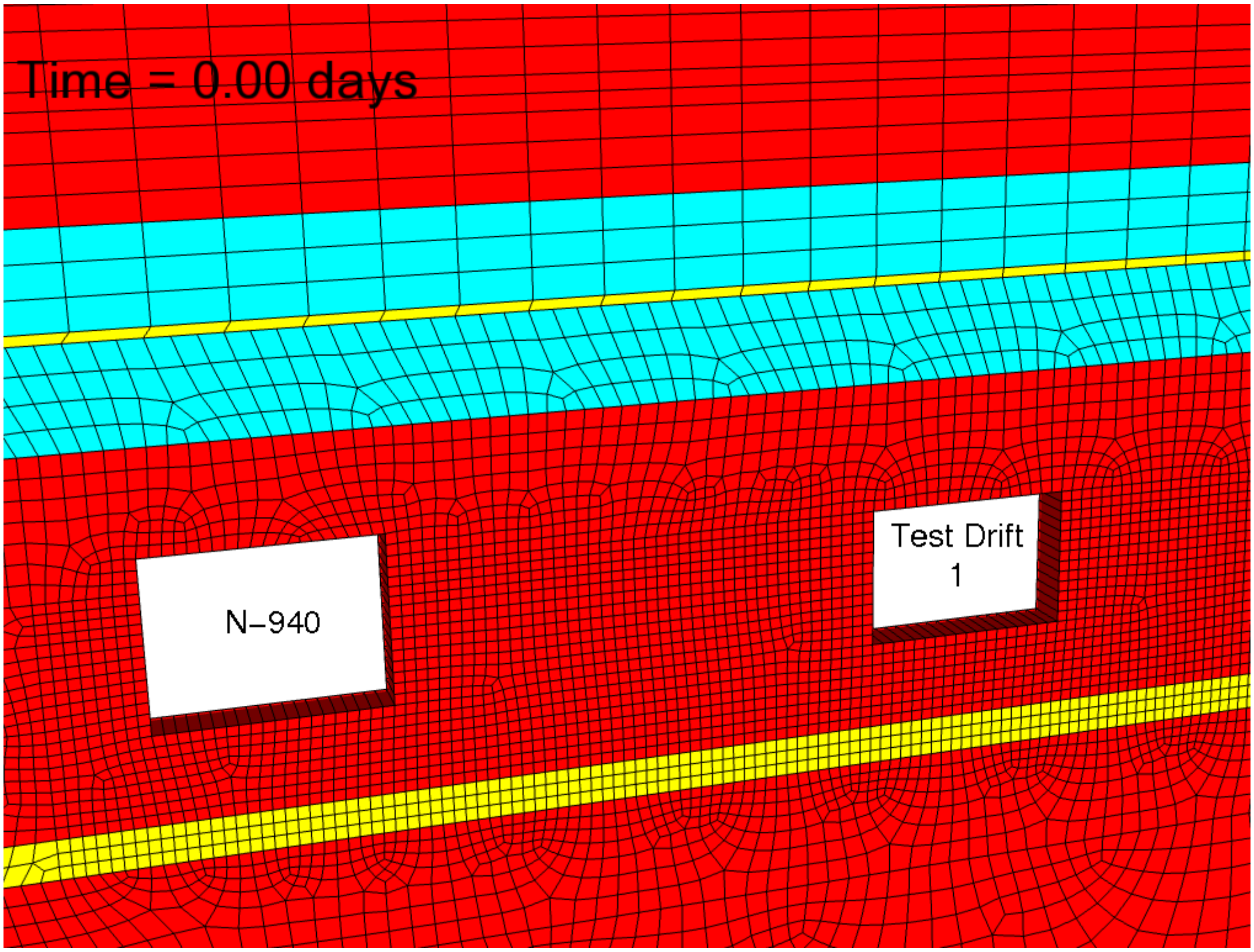

Figure 5: Mesh Detail around Access Drift N-940 and Test Drift 1.
Red is argillaceous halite, yellow is anhydrite, and teal is clean halite.

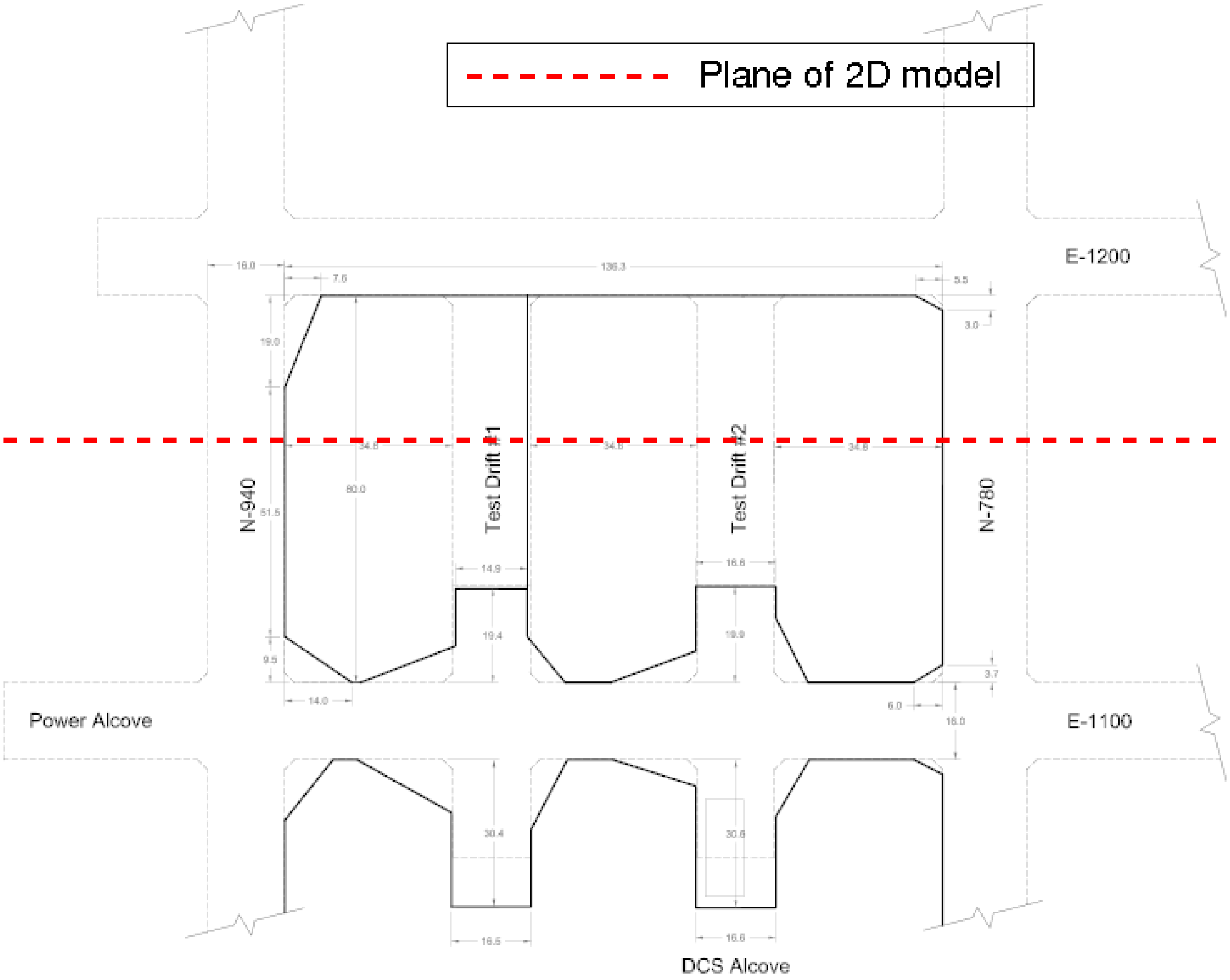

Figure 6: Plan view of access and test drifts.

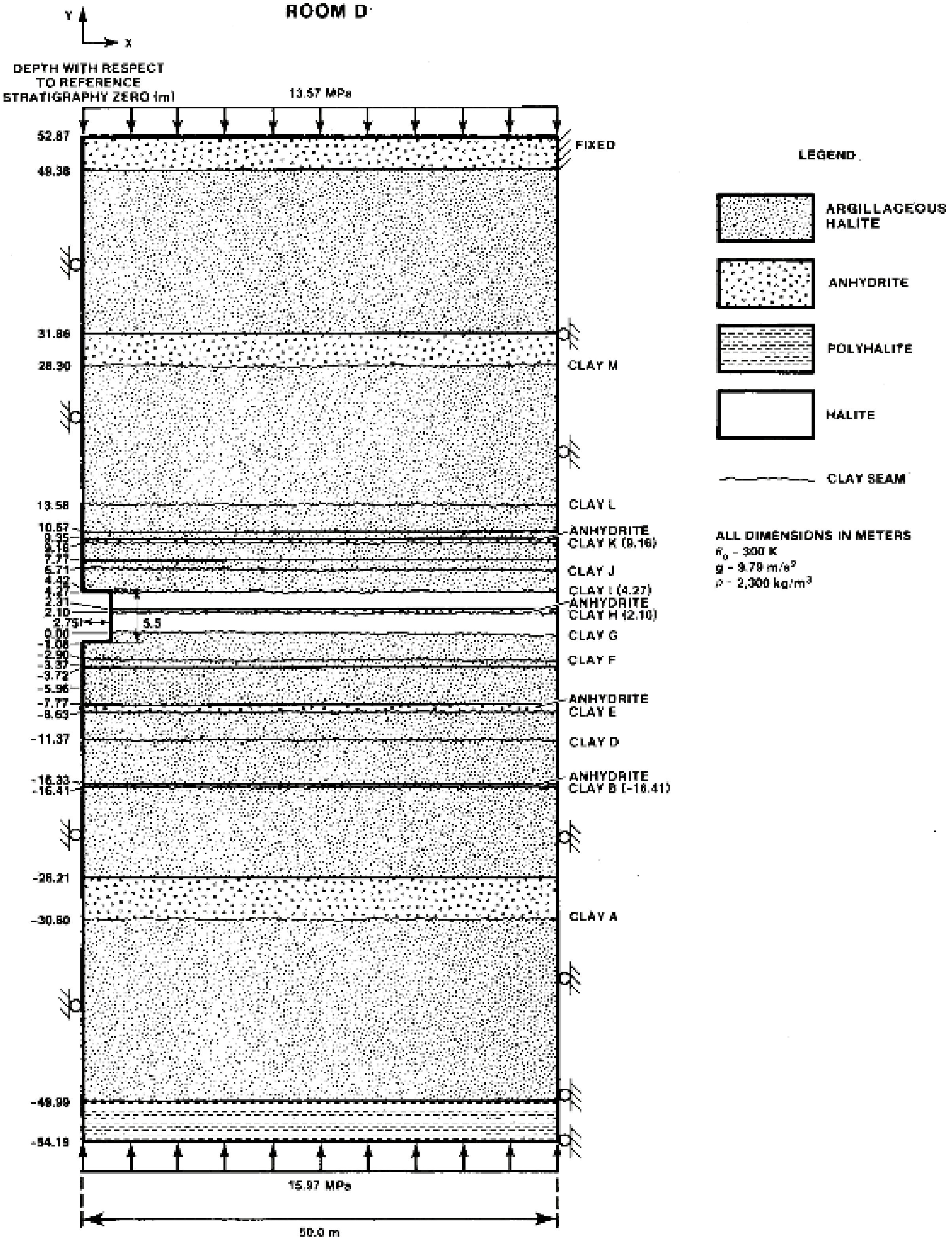

Figure 7: Typical Bedded Salt Stratigraphy from WIPP Room D

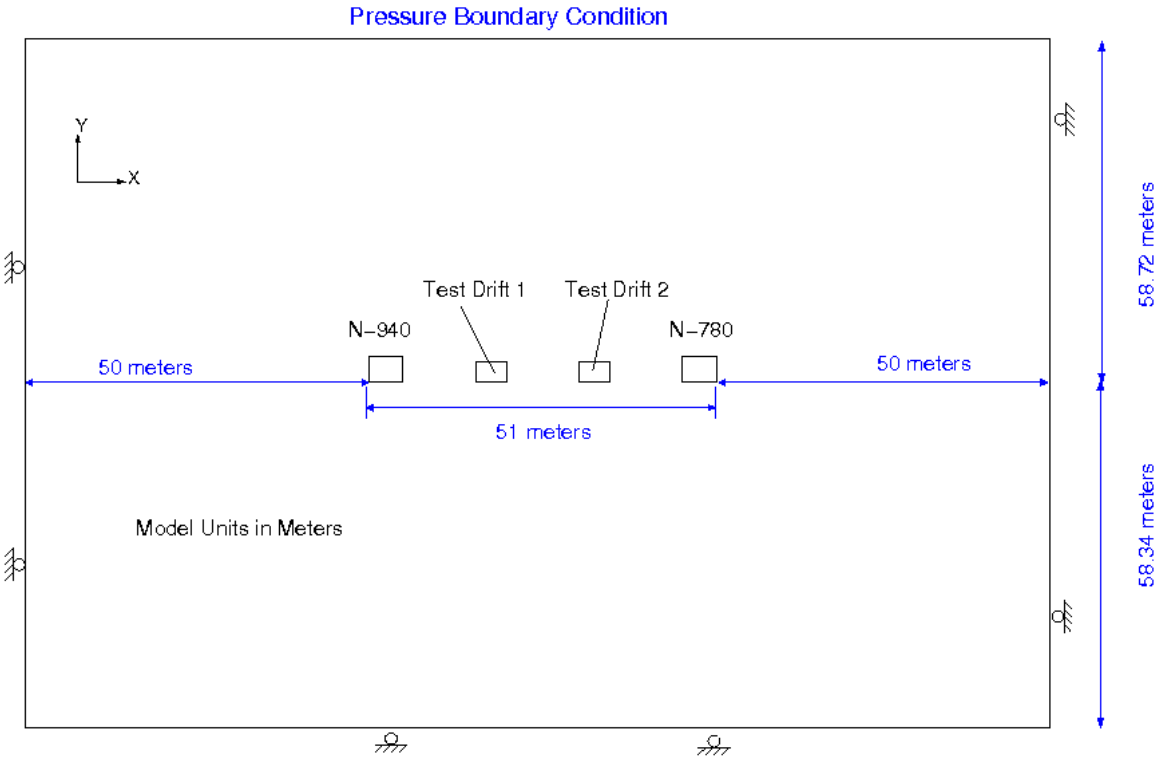

Figure 8: Finite Element Model Boundary Conditions

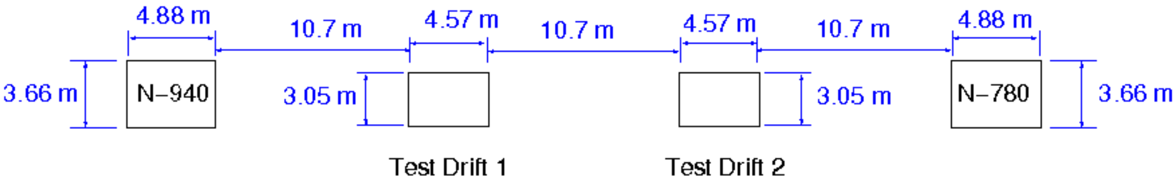

Figure 9: Detail of geometry around the drifts.

The drifts are modeled as open voids in the finite element model with an initial pressure gradient applied to the inner surfaces equal to the lithostatic pressure at the drift elevations. The drifts are mined by linearly reducing the pressure over time to zero. It is assumed it takes 30 days to excavate a drift. Test drift 2 was included in the model, but was not excavated. The sliding interfaces in the WIPP stratigraphy are modeled as non-slipping in this calculation.

Material Properties

The material properties used in the model are listed in Tables 1 to 6. The clean halite and argillaceous salt are modeled using the md-creep material model (i.e., the multi-mechanism deformation model of Munson and Dawson (1979)). The polyhalite and anhydrite are modeled using the soil and crushable foam material model. The salt is assumed to be at a uniform temperature (T) of 300 degrees Kelvin.

Variable	**Value**	**Units**
Density	2300.	kg/m^3
Shear Modulus	12.4×10^9	Pa
Poisson's ratio	0.25	---
A1	8.386×10^{22}	sec^{-1}
Q1/RT	41.94	$Kelvin^{-1}$
N1	5.5	---
B1	6.086×10^6	sec^{-1}
A2	9.672×10^{12}	sec^{-1}
Q2/RT	16.78	$Kelvin^{-1}$
N2	5.0	---
B2	3.034×10^{-2}	sec^{-1}
sig0	2.057×10^7	Pa
Qlc	5335.	---
M	3.0	---
K0	6.27×10^5	---
CT	2.759	---
Alpha	-17.37	---
Beta	-7.738	---
Delta1C	0.58	---

Table 1: MD Salt properties for Clean Salt

Variable	**Value**	**Units**
Density	2300.	kg/m^3
Shear Modulus	12.4×10^{9}	Pa
Poisson's ratio	0.25	---
A1	1.407×10^{23}	sec^{-1}
Q1/RT	41.94	Kelvin^{-1}
N1	5.5	---
B1	8.998×10^{6}	sec^{-1}
A2	1.314×10^{13}	sec^{-1}
Q2/RT	16.78	Kelvin^{-1}
N2	5.0	---
B2	4.289×10^{-2}	sec^{-1}
sig0	2.057×10^{7}	Pa
Qlc	5335.	---
M	3.0	---
K0	2.470×10^{6}	---
CT	2.759	---
Alpha	-14.96	---
Beta	-7.738	---
Delta1C	0.58	---

Table 2: MD Salt properties for Argillaceous Salt

Variable	**Value**	**Units**
Density	2300.	kg/m^3
Young's Modulus	7.51×10^{10}	Pa
Poisson's ratio	0.35	---
A0	2338268.59	Pa
A1	2.33826859	---
A2	0.0	Pa^{-1}
Pressure cutoff	1.0×10^{6}	Pa
Pressure function	Anhydrite Pressure Volumetric Strain Function (see Table 5)	

Table 3: Soil and crushable foam properties for Anhydrite

Variable	Value	Units
Density	2300.	$\mathrm{kg/m^3}$
Young's Modulus	5.53×10^{10}	Pa
Poisson's ratio	0.36	---
A0	2459512.147	Pa
A1	2.457780096	---
A2	0.0	$\mathrm{Pa^{-1}}$
Pressure cutoff	1.0×10^{6}	Pa
Pressure function	Polyhalite Pressure Volumetric Strain Function (see Table 6)	

Table 4: Soil and crushable foam properties for Polyhalite

Volumetric Strain $(\mathrm{m/m})^3$	Pressure (Pa)
-1.0	$-8.344444444\times10^{10}$
0.0	0.0
1.0	8.344444444×10^{10}

Table 5: Pressure and Volumetric Strain function for Anhydrite

Volumetric Strain $(\mathrm{m/m})^3$	Pressure (Pa)
-1.0	$-6.583333333\times10^{10}$
0.0	0.0
1.0	6.583333333×10^{10}

Table 6: Pressure and Volumetric Strain function for Polyhalite

Model Time-Line

The drift excavations are assumed to take 30 days. Time periods between access drift excavations are based on the mining schedule reported for drifts N-940 and N-780 at WIPP (assumed typical for an underground research laboratory in salt), and an assumed time period as for TD1. The model time line is shown in Table 7. The choices of time lags between the start of excavation of drift TD1 (2 years) and the start of the thermal experiments in drift TD1 (3 years) represent educated guesses on unexpected delays in mining and experiment scheduling.

Time (days)	Description
0.	Start of excavation of access drift N-780
30.	Drift N-780 excavation finished.
92.	Start of excavation of access drift N-940
122	Drift N-940 excavation finished.
852	Start of excavation of TD1 (after 2 years wait)
887	TD1 excavation finished.
1,977	Drifts remain open for 3 years isothermally.

Table 7: Mining Sequence of Drifts

<u>Results from the Completed Calculation</u>

Figures 5 through 7 show color contour plots of the damage factor around drift N-940 and TD1. The damage factor is computed as $DF = \frac{\sqrt{J_{2D}}}{0.27I_1}$ when the $DF \geq 1.0$ micro-fracturing in the salt will occur. J_{2d} is the second invariant of the deviatoric stress tensor (related to the octahedral shear stress) and I_1 is the first invariant of the stress tensor (related to confining stress or pressure). Figure 5 shows damage immediately after the test room is excavated (122 days).

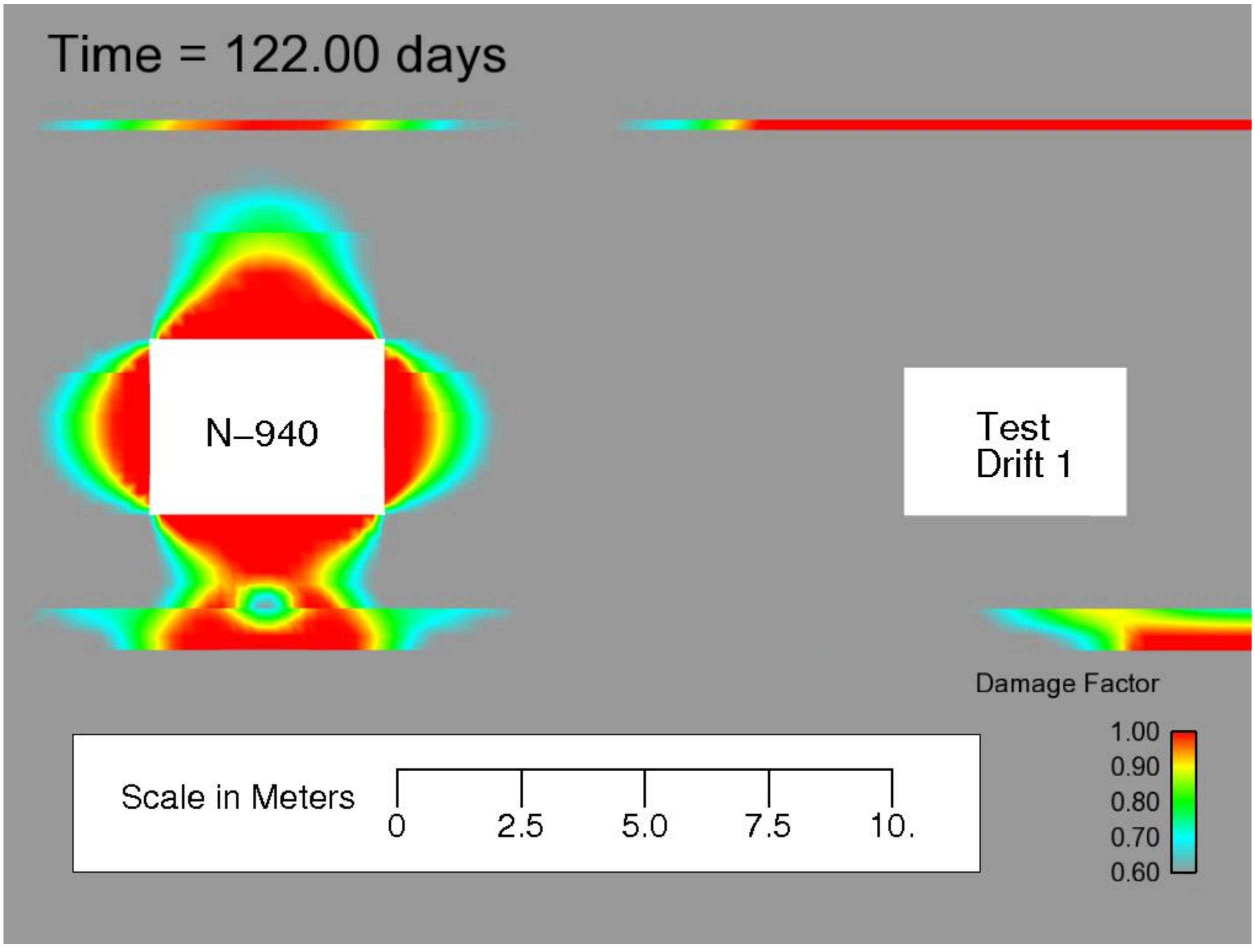

Figure 10: Damage Factor Contours after the Drift N-940 is excavated.

Once the drifts are excavated the extent of the damage zones around the drifts change little over time. The horizontal banding in the damage zone below the drifts corresponds to marker bed 139 and the band above the drifts corresponds to an anhydrite layer (see Figure 2 for stratigraphy). These layers would not damage in the same ratio of stress invariants as salt, so no particular significance is attributed to these contours.

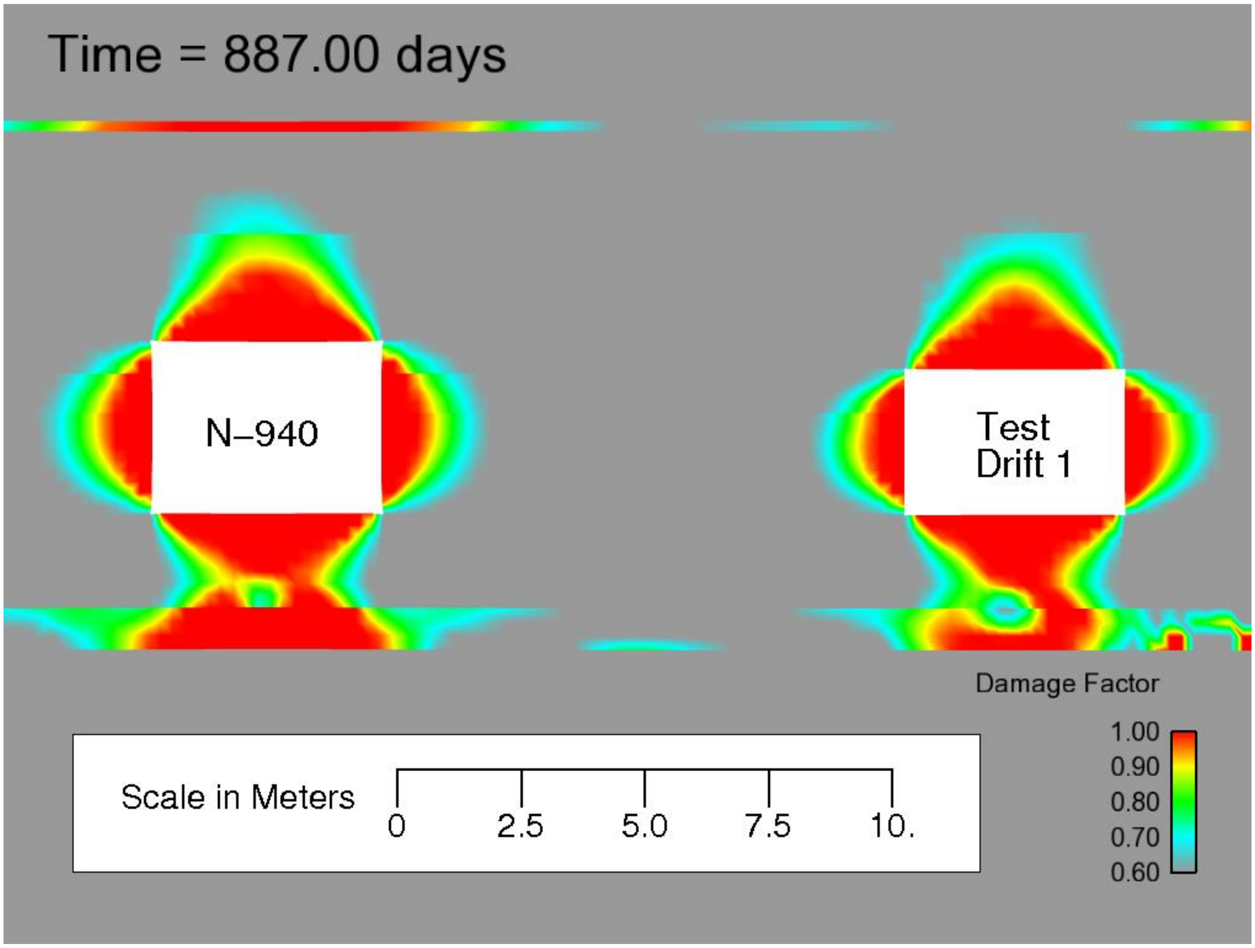

Figure 11: Damage Factor Contours after TD1 excavation is completed.

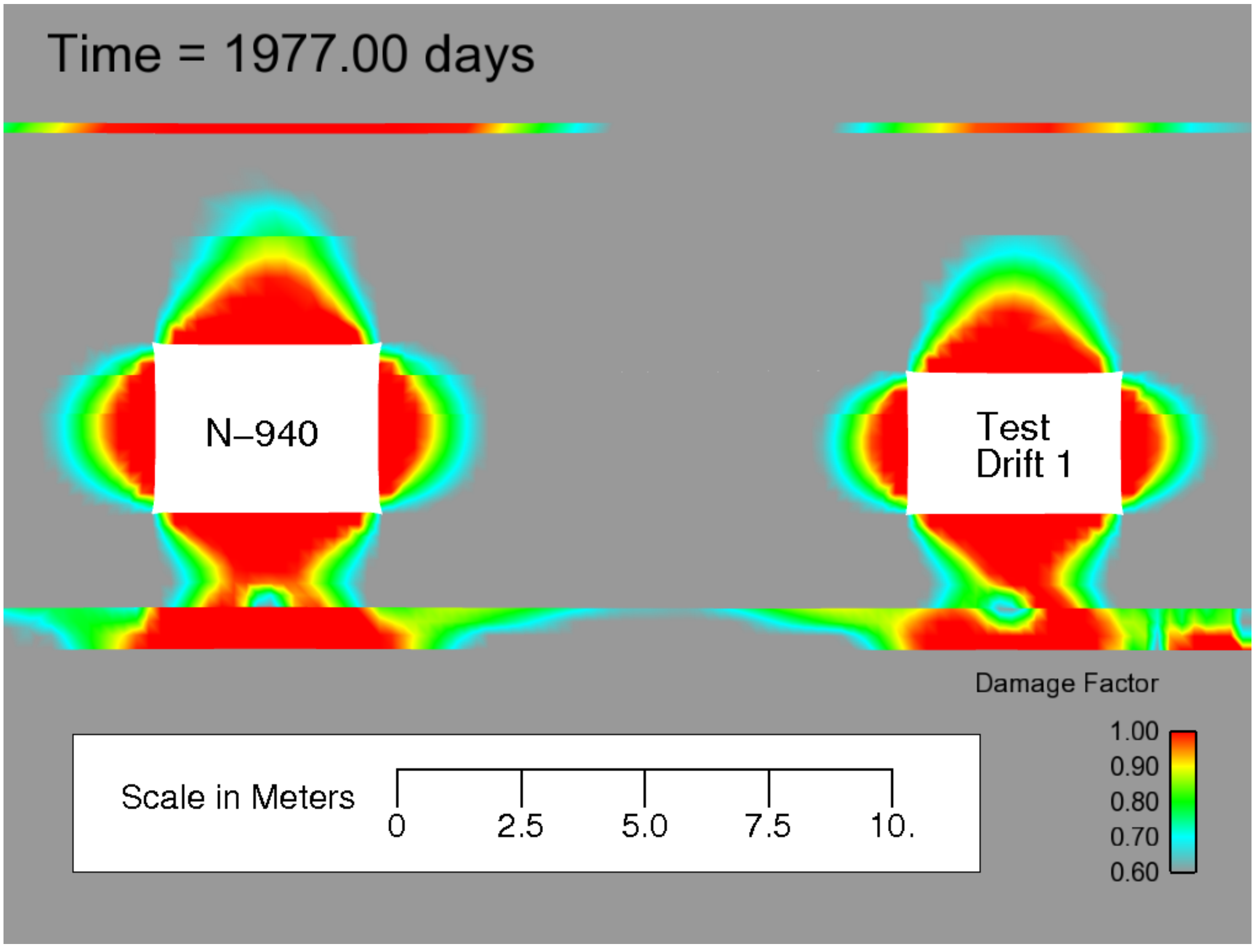

Figure 12: Damage Factor Contours 3 years after TD1 excavation is completed.

Probe Locations

To provide an estimate of the temporal change in the displacement field between the drifts a horizontal line of displacement probe are assumed between drift N-940 and TD1. Figure 9 shows the locations of the probes. Time histories of the horizontal displacements at the probe locations are shown in Figure 10.

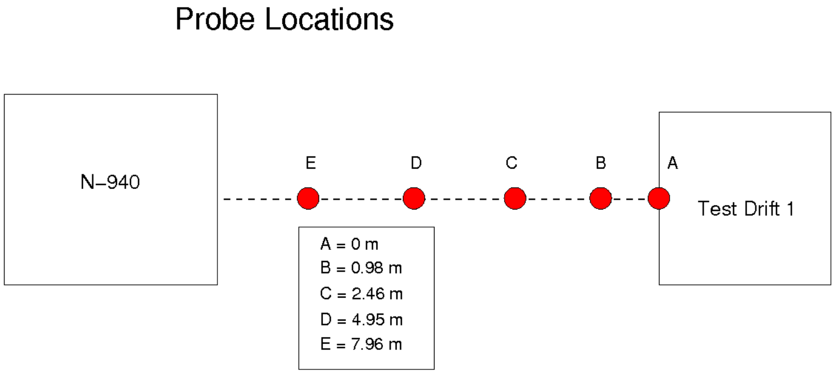

Figure 13: Displacement Probe Locations

A positive value of the displacement means the probe location is moving towards TD1. It is assumed the probes are installed immediately after the excavation of drift N-940.

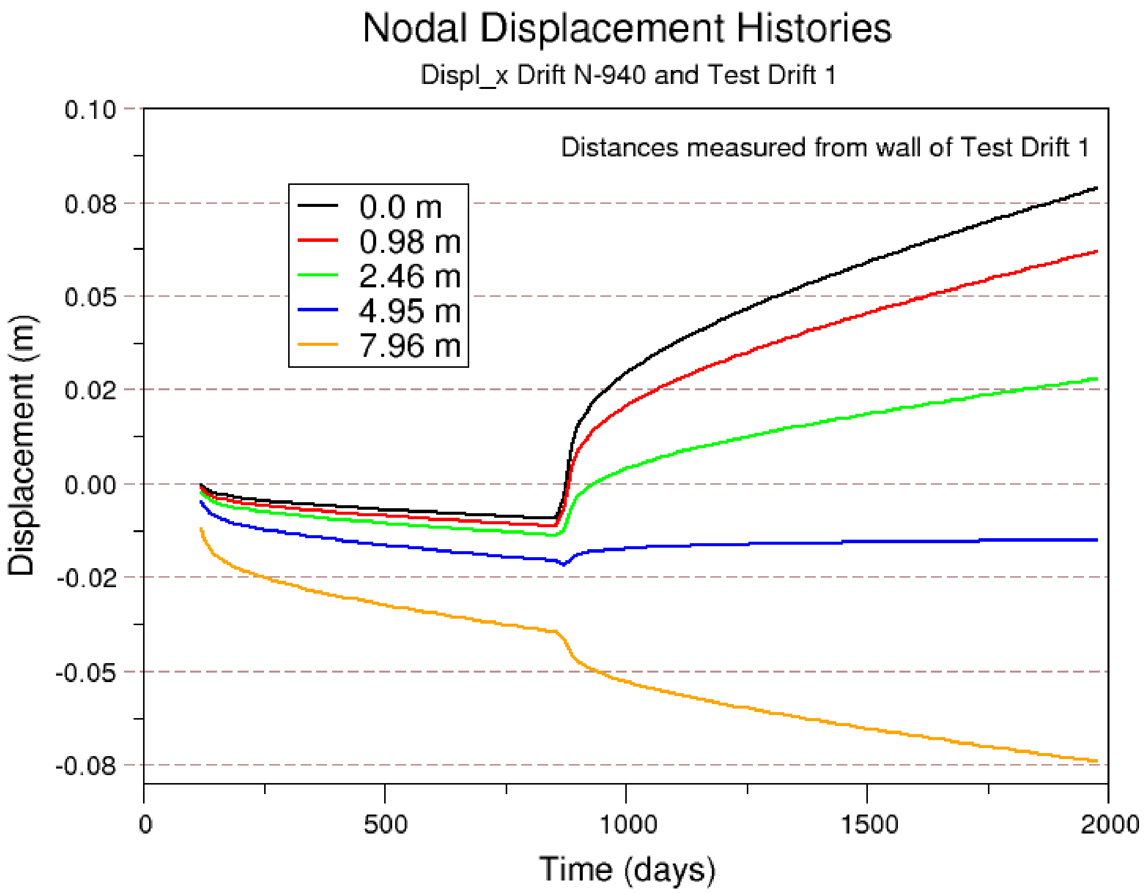

Figure 14: Displacement Histories at the Probe Locations shown in Figure 9.

The “kink” in the displacement history curves occurs when TD1 is excavated. Probe locations five meters or greater from the wall of TD1 show the influence of the displacement field around drift N-940.

Based on these calculations, the extensometers should have an anchor set at 0.5 m from the excavation wall with a measurement range of 0.10 m, double the expected displacement. The outer anchor would be set at about 5 m, which is approximately neutral between the two drifts. Displacement precision should finer than 0.001 m (1 mm). Off-the-shelf extensometers are typically more sensitive than +/- 0.001 m. Final arrangements and gauge selection would be determined by the Principal Investigator.

Appendix E

Flow-down of Quality Assurance Requirements

Organization

Sandia National Laboratories' organization is fully described on the Sandia Internal Website (Techweb). The activities described in this Test Plan are the responsibility of Organization 06224 (Applied Systems Analysis and Research), within SNL's Nuclear Energy and Fuel Cycle Programs (06200). Figure E-1 shows the QA requirements interfaces for the activity.

This R&D activity, managed as Work Package FT-14SN081805, is conducted by Sandia National Laboratories under contract to U.S. DOE as part of the DOE-NE Fuel Cycle Technologies (FCT) program Used Fuel Disposition (UFD) Campaign. As an FCT UFD R&D activity, it is conducted in accordance with the FCT QAPD[2], SNL's DOE approved QA Program Description (SNL-QAPD)[3] and SNL's UFDC Quality Assurance Implementation Plan[4] (SNL-UFCD-QAIP). Management decided to augment basic requirements for this QRL3 activity, based on the potential utility of the results. The Work Package Manager met with the FCT QA POC on September 4, 2014 to grade the QA requirements for this activity. The results of the grading are presented in Table E-1. Hence, this Appendix to the activity Test Plan is provided in compliance with the provisions of SNL-UFCD-QAIP Section 4.

Quality Assurance Program

To summarize the minimum requirements for this QRL3 activity, as described in SNL-UFCD-QAIP, the activity is to be conducted in compliance with the SNL-QAPD, with the additional requirement that deliverables receive a technical review in accordance with the FCT QAPD Appendix B.

Management decided that certain quality assurance improvements would be beneficial to the conduct of this activity. Table E-1 reflects the outcome of QA grading considerations.

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[2] U.S Department of Energy, Office of Nuclear Energy, Fuel Cycle Technologies Quality Assurance Program Document, Washington, D.C., December 20, 2012.

[3] Sandia's Quality Assurance Program Description SNL-QAPD-2014-05-30, Rev:4.0 May, 30, 2014

[4] Sandia National Laboratories Used Fuel Disposition Campaign Quality Assurance Implementation Plan; Fuel Cycle Research & Development; Prepared for U.S. Department of Energy Used Fuel Disposition Campaign December 2010 FCR&D-USED-2011-000019 Revision 1; February 15, 2013.

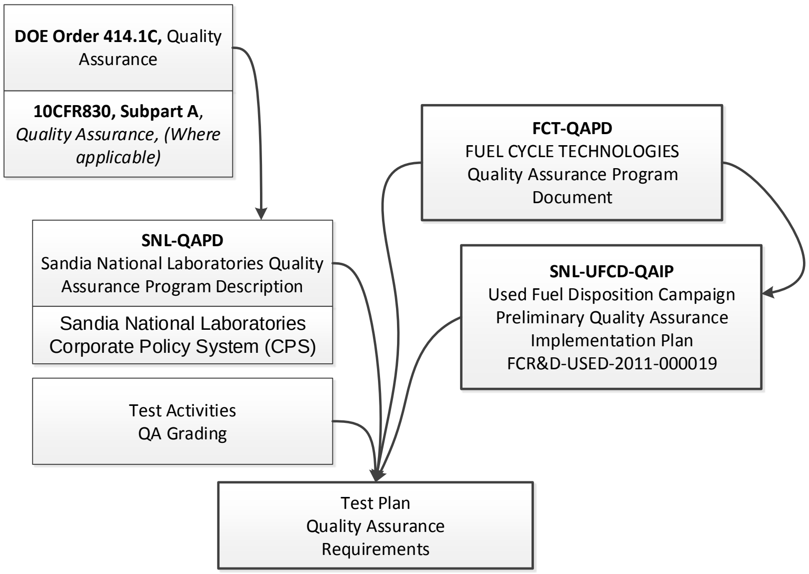

Figure E-1. General QA Requirements Flow Down for Activities.

Quality Assurance requirements flow down from the FCT QAPD, the SNL-QAPD and SNL-UFCD-QAIP, as illustrated in Figure E-1. Predominantly, procedures from the Sandia Corporate Policy System (CPS) apply to this activity's quality elements, consistent with the approved SNL-QAPD. In selected instances, specific procedures are needed to improve quality to approximate NQA-1 levels for certain quality elements. Table E-1 identifies the CPS procedures that are generally applicable as well as the specific procedural augmentations that apply.

Table E-1. Graded Quality Assurance Requirements for Test Plan Activity

NQA-1 (2008) Requirement Excerpt[5]	**Summary of Grading**	**Procedures as Appropriate**
Organization - Responsibilities for the establishment and implementation of the quality assurance program shall be defined. The organizational structure, functional responsibilities, levels of authority, and lines of communications for activities affecting quality hall be documented.	A description of performing organizations placement within laboratory organization, including interfaces, is provided above. Rely on CPS procedures, including those listed in adjacent column, as appropriate. Testing is will be conducted in a facility not operated by Sandia. Section 4.1.10 addresses Coordination with other Organizations and will need to be updated to reflect the circumstances at the time work is started.	**CG 100.1** - Establish the Decision-Making Framework **CG 100.1.1** - Create and Maintain the Mgmt. Structure **CG 100.1.2** - Create or Change a Policy - Process - or Procedure **CG100.6.19** - Conduct Management Review

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[5] Refer to ASME NQA-1-2008 (Revision of ASME NQA-1-2004) Quality Assurance Requirements for Nuclear Facility Applications for complete description of requirement.

Quality Assurance Program - The program shall identify the activities and items to which it applies. The program shall provide control over activities affecting quality to an extent consistent with their importance.	A description of the Quality Assurance Program, requirements flow down, relationships between FCT QA, NNSA/SFO QA and laboratory QA organizations, is provided above. Rely on CPS procedures, including those listed in adjacent column, as appropriate. Specific qualifications and training required of MOW involved in the activity are addressed by the specific FCT QAP identified. This is an FCT UFD activity and will be conducted under the Laboratory's QA program consistent with the Fuel Cycle Technologies Quality Assurance Program Document Revision 2 (FCT-QAPD). No changes recommended to grading for this QA element.	Multiple CPS procedures in **HR100.2**. **FCT QAP 2-1** Qualification and Training
Design Control - The design shall be defined, controlled, and verified. Design inputs shall be specified on a timely basis and translated into design documents. Design interfaces shall be identified and controlled. **(Note: Includes provisions applicable to use of computer programs.)**	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Related controls are addressed by the specific FCT QAP identified. No specific design work contemplated. Procedures for Software Qualification as described in Section 4.3.5 will need to be developed before the Software is developed.	**CG100.8.1 -** Perform Work **CG100.8.2 –** Manage Projects Throughout Their Lifecycle **CG100.8.3 -** Apply Configuration Management Principles to Documents and Physical Items **FCT QAP 20-1** Test Plans
Procurement Document Control - Applicable design bases and other requirements necessary to assure adequate quality shall be included or referenced in documents for procurement of items and services. To the extent necessary, procurement documents shall require Suppliers to have a quality	Rely on CPS procedures, including those listed in adjacent column, as appropriate. No procurements requiring specifications beyond those typically provided by the Laboratory are contemplated. No changes recommended to grading for this QA element.	Multiple procedures in **SCM100** – Manage Property, Material and Services through the Supply Chain

assurance program consistent with the applicable requirements of NQA-1.		
Instructions, Procedures and Drawings - Activities affecting quality and services shall be prescribed by and performed in accordance with documented instructions, procedures, or drawings that include or reference appropriate quantitative or qualitative acceptance criteria for determining that prescribed activities have been satisfactorily accomplished.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Procedures to be used or developed are specified in Section 4.1.5 of the Test Plan. This QA element will need to be updated to reflect the procedures necessary for the work before work is started.	**CG100.1.2 -** Create or Change a Policy - Process - or Procedure **FCT QAP 5-1** Implementing Procedures
Document Control - The preparation, issue, and change of documents that specify quality requirements or prescribe activities affecting quality such as instructions, procedures, and drawings shall be controlled to ensure that correct documents are being employed.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. FCT QAPs listed will be modified to rely mostly on CPS, to provide explicit information for the task. Current Laboratory protocols and FCT Procedures are adequate for the work proposed. No changes recommended to grading for this QA element.	**IM100.2.1 -** Control of Documents **IM100.2.2 -** Control of Records **HR100.2.15 -** Maintain Training Records in TEDS LMS **HR100.5.7 -** Manage Corporate Human Resources Records **FCT QAP 6-1** Document Review Process **FCT QAP 6-2** Document Control
Control of Purchased Items and Services - The procurement of items and services shall be controlled to ensure conformance with specified requirements.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	**ME100.3.1CG100.8.1 -** Perform Work **SCM100.2.2 -** Acquire Property (Requirements and Instructions - Inspect and Return Property section)**SCM100.3.10 -** Do’s and Don’ts for Requesters and SDRs During Contract Management Activities (Requirements and Instructions - step 3)
Identification and Control of Items - Controls shall be established to assure that only correct and accepted items are	Rely on CPS procedures, including those listed in adjacent column, as appropriate.	**ME100.3.1 CG100.8.1 -** Perform Work **SCM100.2.2 -** Acquire Property (Requirements

used or installed.	Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	and Instructions - Inspect and Return Property section) **SCM100.3.3** – Manage Property **SCM100.3.10 -** Do's and Don'ts for Requesters and SDRs During Contract Management Activities (Requirements and Instructions - step 3) **SCM100.3.13** – Manage Suspect or Counterfeit Items **SCM100.3.14 -** Store General Materials at Sandia National Laboratories
Control of Special Processes - Special processes that control or verify quality, such as those used in welding, heat treating, and nondestructive examination, shall be performed by qualified personnel using qualified procedures in accordance with specified requirements.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. No special processes are contemplated. Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element. Additional controls are addressed by the FCT QAP identified.	**ME100.3.1 CG100.8.1 -** Perform Work **FCT QAP 9-1** Analysis
Inspection - Inspections required to verify conformance of an item or activity to specified requirements or continued acceptability of items in service shall be planned and executed.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	**ME100.3.1 CG100.8.1 -** Perform Work **SCM100.2.2 -** Acquire Property (Requirements and Instructions - Inspect and Return Property section) **SCM100.3.10 -** Do's and Don'ts for Requesters and SDRs During Contract Management Activities (Requirements and Instructions - step 3) **SCM100.3.13** – Manage Suspect or Counterfeit Items
Test Control - Tests required to collect data such as for	Activity specific controls are addressed by the FCT QAPs	**FCT QAP 20-1** Test Plans **FCT QAP 20-2** Scientific

siting or design input, to verify conformance of an item or computer program to specified requirements, or to demonstrate satisfactory performance for service shall be planned and executed. **(Note: Applicable to testing of computer programs, hardware and operating systems.)**	identified. Note: Requirements specifically identified for software determined to be N/A, because of the nature and use of data recording and later processing. Current Laboratory protocols and FCT Procedures are adequate for the work proposed. No changes recommended to grading for this QA element.	Notebooks
Control of Measuring and Test Equipment - Tools, gauges, instruments, and other measuring and test equipment used for activities affecting quality shall be controlled, calibrated at specific periods, adjusted, and maintained to required accuracy limits.	Rely on CPS procedures, including those listed in adjacent column, which requires a measurement assurance plan consistent with Primary Standards Lab (PSL) practices. Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	**ME100.3.1 CG100.8.1 -** Perform Work
Handling, Storage and Shipping - Handling, storage, cleaning, packaging, shipping, and preservation of items shall be controlled to prevent damage or loss and to minimize deterioration.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Additional controls are addressed by the FCT QAP / FCT SPs identified. Current Laboratory protocols and FCT Procedures are adequate for the work proposed. No changes recommended to grading for this QA element.	**SCM100.3.3** – Manage Property **SCM100.3.14 -** Store General Materials at Sandia National Laboratories **FCT QAP-13-1** Control of Samples **FCT SP-13-1** Chain of Custody
Inspection, Test, and Operating Status - The status of inspection and test activities shall be identified either on the items or in documents traceable to the items where it is necessary to ensure that required inspections and tests are performed and to ensure that	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	**ME100.3.1 CG100.8.1 -** Perform Work **CG100.5.5 -** Control Item and Process Nonconformances **SCM100.3.13 -** Manage Suspect or Counterfeit Items

items that have not passed the required inspections and tests are not inadvertently installed, used, or operated.		
Control of Nonconforming Items – Items that do not conform to specified requirements shall be controlled to prevent inadvertent installation or use.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Not applicable for R&D activity (NQA-1 2008 Subpart 4.2 Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development)	**SCM100.3.13 -** Manage Suspect or Counterfeit Items **CG100.6.6 -** Perform Corrective Action **CG100.6.9 -** Conduct Root Cause Analysis and Extent of Condition Reviews **CG100.5.5 -** Control Item and Process Nonconformances
Corrective Action - Conditions adverse to quality shall be identified promptly and corrected as soon as practicable. In the case of a significant condition adverse to quality, the cause of the condition shall be determined and corrective action taken to preclude recurrence.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Sandia’s Assurance Information System (AIS) will be used for identification and corrective action of conditions adverse to quality.	**CG100.6.6** - Determine and Take Action
Quality Assurance Records - The control of quality assurance records shall be established consistently with the schedule for accomplishing work activities. Quality assurance records shall furnish documentary evidence that items or activities meet specified quality requirements. Quality assurance records shall be identified, generated, authenticated, and maintained, and their final disposition specified.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Transitory working information and non-record materials will be managed in the ANEP SharePoint site. The ANEP SharePoint site will be used for interim storage of records for convenience FCT deliverables and associated records will be managed in accordance with the FCT Records Management Plan upon finalization of the deliverable. (Submittal of records to the Fuel Cycle Research and Development Document Management System will maintain the associations between deliverables and supporting documentation, to the	**IM100.2.1 -** Control of Documents **IM100.2.2-** Control of Records **IM100.2.3 -** Prepare and Release Information **IM100.2.5-** Identify and Protect Unclassified Information

	extent practicable.) Current Laboratory protocols are adequate for the work proposed. No changes recommended to grading for this QA element.	
Audits - Audits shall be performed to verify compliance to quality assurance program requirements, to verify that performance criteria are met, and to determine the effectiveness of the program. Audit results shall be documented and reported to and reviewed by responsible management. Follow-up action shall be taken where indicated.	Rely on CPS procedures, including those listed in adjacent column, as appropriate. Note: It was determined that auditing the activity was not considered as value added, surveillance/assessment was considered adequate. Assessments will be conducted and entered in the Laboratory's Assurance Information System (AIS).	**CG100.6.3 -** Plan and Perform Assessments **CG100.6.7 -** Conduct and Manage Audits

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