



Salt Heater Test (FY19)

Spent Fuel and Waste Disposition

***Prepared for
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***Sandia National Laboratories
Melissa Mills, Kris Kuhlman, Ed Matteo, Courtney Herrick,
Martin Nemer, Jason Heath, Yongliang Xiong, Matt Paul***

***Los Alamos National Laboratory
Phil Stauffer, Hakim Boukhalfa, Eric Gultinan, Thom Rahn,
Doug Weaver, Brian Dozier, Shawn Otto***

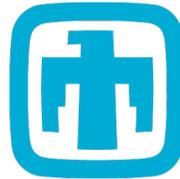
***Lawrence Berkeley National Laboratory
Jonny Rutqvist, Yuxin Wu, Jonathan Ajo-Franklin, Mengsu Hu***

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ACRONYMS

AE	acoustic emissions (also BATS AE boreholes)	MU-0	map unit 0 (WIPP stratigraphic unit)
BATS	brine availability test in salt	NEMA	national electrical manufacturer association
CBFO	Carlsbad field office (DOE-EM WIPP office)	NETL	National Energy Technology Laboratory
CPU	central processing unit	NQA	nuclear quality assurance
CRDS	cavity ring-down spectrometer	PA	performance assessment
CT	computed tomography	PEEK	polyetheretherketone thermoplastic
D	BATS source borehole	POM	polyoxymethylene thermoplastic
DAS	data acquisition system	PVC	polyvinyl chloride plastic
DOE	Department of Energy	R&D	research and development
DOE-EM	DOE Office of Environmental Management	RH	relative humidity
DOE-NE	DOE Office of Nuclear Energy	SDI	Salt Disposal Investigations (proposed CBFO program)
DRZ	disturbed rock zone	SEM	scanning electron microscopy
DSS	distributed strain sensing	SFWST	Spent Fuel & Waste Science & Technology (DOE-NE program)
DTS	distributed temperature sensing	SNL	Sandia National Laboratories
E	BATS ERT boreholes	SL	BATS seal borehole
ERT	electrical resistivity tomography	SM	BATS liquid sampling borehole
F	BATS fiber boreholes	SRS	Stanford Research Systems
FY	fiscal year (October-September)	STP	standard temperature and pressure
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	T	BATS thermocouple boreholes
GWB	G-seep WIPP brine	TCO	WIPP Test Coordination Office
HP	BATS heater/packer borehole	TGA	thermogravimetric analysis
ICP-MS	inductively coupled plasma mass spectrometry	THMC	thermal-hydrological-mechanical-chemical (also THM & THC)
LANL	Los Alamos National Laboratory	UHP	ultra-high purity
LBNL	Lawrence Berkeley National Laboratory	US	United States
LVDT	linear variable differential transformer	WIPP	Waste Isolation Pilot Plant (DOE-EM site)
MB139	marker bed 139 (WIPP stratigraphic unit)	XRD	X-ray diffraction
		XRF	X-ray fluorescence

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SALT HEATER TEST (FY19)

This report discusses the fiscal year 2019 (FY19) design, implementation, and preliminary data interpretation plan for a set of borehole heater tests call the brine availability tests in salt (BATS), which is funded by the DOE Office of Nuclear Energy (DOE-NE) at the Waste Isolation Pilot Plant (WIPP).

The organization of BATS is outlined in *Project Plan: Salt In-Situ Heater Test* (SNL, 2018). An early design of the field test is laid out in Kuhlman et al. (2017), including extensive references to previous field tests, which illustrates aspects of the present test. The previous test plan by Stauffer et al., (2015) places BATS in the context of a multi-year testing strategy, which involves tests of multiple scales and processes, possibly culminating in a drift-scale disposal demonstration.

1. Background and Test Overview

The main focus of BATS is to explore brine availability. These tests are the first part of a wider systematic field investigation campaign to improve the existing long-term repository safety case for disposal of heat-generating radioactive waste in salt. Future tests will explore other aspects of the safety case, as justified by their impacts on long-term performance. These first tests seek to better understand how much brine can flow into an excavation (e.g., borehole or room) in salt. Brine availability is important to the long-term repository safety case for radioactive waste disposal in salt (Kuhlman & Sevougian, 2013) because: 1) brine transport is the primary off-site radionuclide transport vector, 2) brine leads to corrosion of metallic and glass waste forms and waste packages, 3) chloride in brine can reduce criticality concerns, and 4) accumulated brine can provide back-pressure that resists long-term creep closure of porosity associated with mining the repository. In a generic salt repository for “hot” radioactive waste (i.e., above brine boiling temperature at the waste package surface) an area around the hot waste package will dry out, and water vapor will be driven away. Bound water from hydrous minerals can become mobile upon heating, while thermal expansion of intergranular brine drives flow towards excavations at atmospheric pressure. Additionally, a small-scale short-term heat pipe convection process can set up around the waste (Jordan et al., 2015) driving salt precipitation near the waste package and salt dissolution where steam condenses. In the longer-term, creep closure further reconsolidates backfill, closes any gaps around the waste package, and heals the access-drift disturbed rock zone (DRZ) to create a relatively dry, intact, low-permeability zone around the waste packages (Blanco-Martín et al., 2018). Knowledge of brine availability and brine composition facilitates understanding the amount and distribution of brine that flows to an excavation, as well as the long-term behavior of brine around waste packages that affects transport (i.e., brine-radionuclide interactions).

In undisturbed salt disposal systems, the far-field ultra-low permeability and porosity of the salt (Beauheim & Roberts, 2002) provides the primary natural barrier to contain radioactive waste over performance assessment (PA) relevant time scales (10^4 to 10^6 years). However, near-field conditions (e.g., pressures and saturations) and processes (e.g., brine and gas flow, salt creep) will impact releases in an off-normal disturbed scenario and are the initial conditions for a long-term PA simulation. BATS is focused on the quantification of inflow rates and brine composition in the near-field (at scales of cm to m from the heat source) with the aim to improve: 1) our understanding and observations of coupled thermal-hydrological-mechanical-chemical (THMC) processes affecting prediction of near-field conditions; 2) conceptual models of near-field behavior that inform the safety case; and 3) the numerical models, constitutive relationships, and parameterizations that are implemented in PA models.

Brine availability in a salt repository depends on both the properties and distribution of the pore fluid and the properties of the DRZ surrounding an excavation (Kuhlman & Malama, 2013). Pore fluid properties include the original distribution of brine and bound water in the salt formation (i.e., intragranular brine, intergranular brine, hydrous minerals, and intercalated water in clay minerals) and the distribution of water in both the liquid and gas phases during the test. The primary DRZ property of interest for the test is the distribution and evolution of damage (i.e., porosity and permeability of the matrix and induced

fractures) around the access drift and test boreholes, which will likely provide the primary path for flow towards the test boreholes.

The BATS test comprises two initial horizontal borehole heater tests to be conducted in the Salt Disposal Investigation (SDI) area drifts (near N-940 and E-500; see Figure 1) of WIPP. Two arrays of horizontal boreholes are planned (heated and unheated), each to be drilled in the pattern shown in Figure 2.

One test array will be heated (heater in central HP borehole) and the other pattern will be similar, but unheated. Each array will be configured with instruments in the central HP borehole and the surrounding satellite boreholes. Temperature distribution, strain, and brine movement will be monitored with thermocouples, fiber-optic distributed strain (DSS) and temperature (DTS) sensing, acoustic emissions (AE) monitoring, ultrasonic travel-time tomography, electrical resistivity tomography (ERT), introduced liquid and gas phase tracers, and sampling of liquid and vapor phases for natural and introduced tracers (Table 1). The test and a high-level plan for interpreting the data are summarized in Table 2, and are discussed in more detail in the following sections.

Several aspects of the test have been demonstrated and refined as part of a “shakedown test” that was performed (June 2018, continuing through April 2019; Boukhalfa et al., 2018). The dry N₂ gas circulation system, the borehole closure gage, the Drierite desiccant, the LI-COR gas analyzer, the Stanford Research Systems (SRS) gas analyzer, the packer, the grouting of thermocouples, and several revisions of the heater design were tested and implemented as part of the shakedown test. Numerical simulations supporting the shakedown test were used to refine understanding of several components of the system. For example, the original design of the conductive heater block was shown to be inefficient at transferring heat to the rock salt, and a new infrared heater was substituted. The new heater performed to specification and resulted in much greater heat flow into the rock salt surrounding the borehole (Stauffer et al., 2019), better achieving the goals of the test (i.e., exploring brine availability at elevated temperature). The shakedown testing has increased confidence in the upcoming borehole heater tests.

In addition to providing data about brine availability, the unique brine geochemical data to be obtained during the tests are potentially relevant to long-term repository safety cases, including benchmarks for adjusting and validating thermodynamic databases for geochemical modeling of brine chemistry in salt.

Table 1. Summary of boreholes (drift view illustrated in Figure 2)

Type	Purpose	Bores per array	Diameter [in]	Length [ft]	Isolation Device
HP	Heater, packer, borehole closure, N ₂ circulation, gas sampling	1	4.8	12	Inflatable packer
D	Tracer source	1	2.1	15	Inflatable packer
SM	Liquid sampling	1	2.1	15	Expansion plug
F	Fiber-optic	2	1.75	18 & 30	Grouted
E	Electrical resistivity tomography (ERT)	3	1.75	18	Grouted
AE	Acoustic emissions (AE) and ultrasonic travel-time tomography	3	2.1	9	Sensors on borehole wall w/ centralizer
T	Thermocouples	2	1.75	18	Grouted
SL	Cement seals	1	4.8	8	Expansion plug

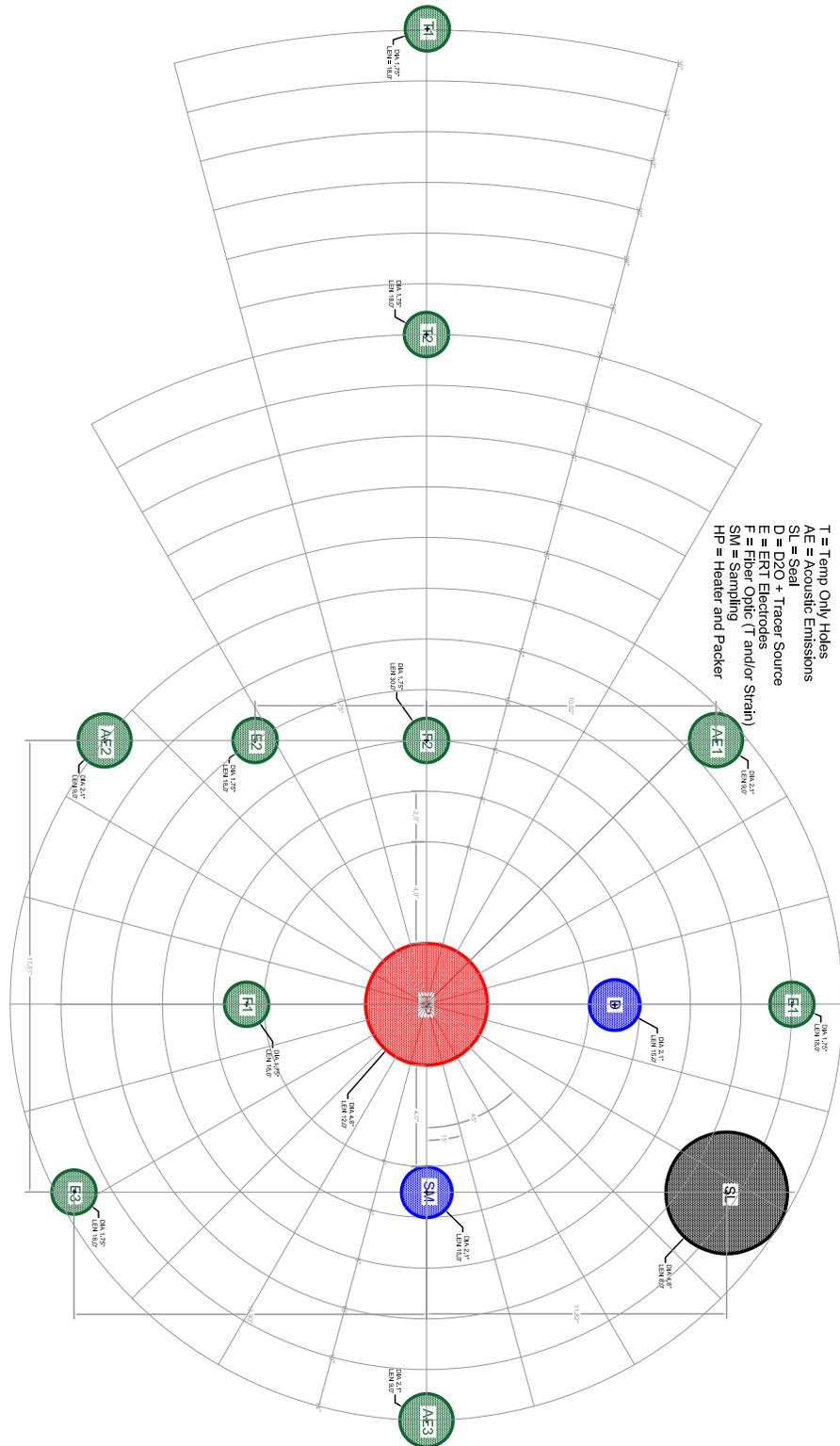


Figure 2. Borehole layout for each test array (one heated, one unheated)

Table 2. Summary of data to be collected in BATS

Goal	Data	Location	Benefit
Estimate amount of brine in salt	Core analyses: X-ray CT, microscopic analyses, TGA analyses	HP, SL boreholes (heated and unheated arrays) and post-test cores	Quantify initial brine distribution in salt, including its disposition (e.g., intergranular vs. intragranular).
Observe changes in temporal distribution of three types of water in salt with temperature	HP water vapor and isotopic makeup time series, brine composition samples	Continuous gas stream analysis in HP boreholes, and liquid brine samples in SM boreholes (heated and unheated arrays)	Quantify initial conditions for long-term PA models (e.g., damage, pressure, saturation). Three water types differ in long-term mobility.
Estimate distribution of damage around access drift	Gas permeability testing pre- and post-heating; induced fracture characterization	HP, SL, D & SM boreholes (heated and unheated arrays)	Pre-existing damage is main source of permeability and porosity in salt
Use geophysics to track 4D evolution of brine during heating	ERT and ultrasonic travel-time tomograms	ERT and AE boreholes (heated and unheated arrays) will be sensitive to brine and porosity distribution around HP boreholes	Changes in brine content and porosity due to damage and dry out are inputs to PA models and verify conceptual models
Monitor gas-phase transport through salt	Breakthrough of gas-phase tracers	Four gas tracers introduced to D borehole, monitored in HP borehole real-time (heated and unheated arrays)	Point-to-point tracer tests provide best controls on advective (gas-filled) porosity and tortuosity
Monitor liquid-phase transport through salt	Breakthrough of water and liquid-phase tracers	Two liquid tracers, and isotopically light water introduced to D borehole, monitored in HP borehole real-time (heated and unheated arrays)	Point-to-point tracer tests provide best controls on advective (liquid-filled) porosity and tortuosity
Monitor deformation and damage accumulation in salt	AE time/location distribution, borehole closure, 3D stress state, longitudinal strain along fiber	Borehole closure in HP, plug strain in SL, and longitudinal strain F2. AE triangulated from observations in AE boreholes (heated and unheated arrays)	Mechanical damage and healing are main changes of permeability and porosity. Need to understand/predict significant damage that happen when heater is switched on/off
Estimate temperature distribution	Temperature distribution and energy input at heater	Heat source applied in HP (heated array only), temperature distribution in thermocouples (HP, T, AE, E, and F), thermistors (SL), and distributed temperature sensing fiber-optics (F) in both heated and unheated arrays	Thermal properties of salt, and thermal "drive" of hydrological and mechanical systems
Observe salt/cement interactions	Microscopic, X-ray CT, and compositional analyses on overcore samples of exposed cement seals	SL borehole (heated and unheated arrays)	Explore stability of juxtaposed materials and understand/predict interactions between salt, brine, and cementitious materials under repository relevant conditions.

2. Testing Plan Details

The following details relate to the construction and instrumentation of the test in general. The description of individual boreholes and their instrumentation is presented in Section 3.

2.1 Horizontal Borehole Drilling and Coring

The horizontal boreholes of each array will be drilled at the specified diameters, locations, and orientations indicated in Figure 2 (horizontal boreholes will deviate downward an inch or two over their length, which is acceptable and allows produced brine to accumulate at the far ends of the boreholes). After completion of each borehole, a plug (i.e., a sewer plug or small mechanical packer) will be installed to minimize evaporation of brine from boreholes into the mine ventilation. The plug will be inserted whenever other activities are not being conducted in the boreholes. The actual as-built location of the boreholes at the drift face will be documented with surveying techniques.

After drilling is complete, the center line of each borehole will be measured, and an as-built drawing will be produced with the actual patterns. The straightness and dip of each borehole will be assessed with available levels and tools and will be included on the drawing. Each of the boreholes will be cleaned to remove cuttings and any brine accumulated in the boreholes before the beginning of the test (quantity of brine inflowing into each borehole will be estimated and compositional samples will be collected). In particular, brine from the HP, SL, D, and SM boreholes will be collected post-drilling and periodically up to instrumentation installation. The pre-test condition of each borehole will be documented with a video inspection camera. If feasible, depth-registered logging or imaging will be used to quantify and document location of observed features, fractures, and non-salt components (e.g., regions of clay or polyhalite). On the rock face at each array, at least one datum bar will be installed with short bolts (a few inches) and adjusted so they are on the same plane. Because the rock face is not exactly flat, these bars will provide the investigators a zero-point to measure from when installing instrumentation into the boreholes and will allow for a consistent depth of instrumentation.

In each of the two near-identical test arrays, there will be a cored central 12-ft [3.7 m] long, 4.8-in [12.2 cm] diameter borehole. In the heated test, this central borehole (HP) will be heated. In both the heated and unheated tests, the HP borehole will have dry nitrogen gas circulated through it. The 4.8 in [12.2 cm] diameter seal borehole (SL) will also be cored. The surrounding satellite boreholes will be drilled using either 2.1-in [5.3 cm] diameter bit (sampling, AE, and source boreholes) or a 1.75-in [4.4 cm] diameter bit (instrumentation boreholes).

2.2 Horizontal Borehole Core

The core from the 4.8-in [12.2 cm] diameter boreholes will be preserved in plastic to prevent dry out and will be documented generally following established WIPP core logging procedures, but nuclear quality assurance (NQA) level-1 quality documentation or procedures are not required for this test. The core will be labeled and put into standard core boxes. The boxed core will be driven to SNL in Albuquerque, where it will be shipped to National Energy Technology Laboratory (NETL) for X-ray CT imaging, optical photography, surface elemental X-ray fluorescence (XRF) surface mapping, P-wave velocity and magnetic susceptibility profiling, and overall documentation. Core will be returned to SNL after testing. Core tests will help constrain the hydrological and mechanical stratigraphy encountered.

2.3 Gas Permeability Testing

Inflatable Aardvark-brand packers will be used to perform constant-flowrate or pressure-decay gas permeability tests on the 2.1-in [5.3 cm] and 4.8-in [12.2 cm] diameter boreholes after drilling. The permeability testing packers are similar size but have fewer pass-throughs than the packers to be installed long-term into the HP boreholes for the gas circulation portion of the test.

The focus of the permeability testing will be to discern the extent of the DRZ surrounding the access drift, rather than mapping the permeability of intact halite (which is likely below the resolution of the setup; Beauheim & Roberts, 2002). Additionally, regions of very high permeability (i.e., through-going open fractures identified in video surveys) can exceed the resolution of the test setup. Permeability testing will be done before installing instruments, to determine the extent of the DRZ surrounding the access drifts, and to ensure that packers are installed so as to provide long-term isolation of the test intervals from the most significant parts of the DRZ.

Constant-pressure permeability tests can be performed in higher-permeability intervals, while pressure-decay permeability tests will be conducted in lower-permeability intervals. During permeability testing, the inflatable packer will be inserted into the borehole to the shallowest practical depth and inflated. The working gas for permeability testing will either be nitrogen or air, delivered from either a bottle or small electric air compressor.

If the interval has high permeability (e.g., close to the drift wall in the DRZ from excavation) a constant-pressure permeability test can be attempted because the initial pressure will decay too quickly for a falling-pressure test. For a constant-pressure test the upstream gas pressure is set at a target value (e.g., 10 psi gage [69 kPa]) and the resulting steady-state gas flowrate is recorded. For purposes of damage delineation, if the permeability of an interval is too high, it simply will be indicated that the interval is above the discernable range and testing will move on to the next interval.

If the interval has low permeability (e.g., deeper into the borehole, further from the excavation DRZ) a falling-pressure permeability test will likely be sufficient. During this type of test, the interval behind the packer is pressurized to a set value (e.g., 30 psi gage [207 kPa]), then the gas source is shut off, and the gas pressure in the line between the packer and the pressure source is monitored at a sufficient frequency for interpretation.

After either type of test is complete the interval behind the packer will be depressurized, the packer will be deflated and moved further back into the borehole, then re-inflated for testing the next interval. This will continue as far back as it is feasible to push the packer. It is expected the apparent gas permeability of the packer-isolated borehole interval will decrease as the packer is moved further back into the borehole, away from the access drift DRZ. Of particular interest will be the permeability of the formation surrounding the HP borehole. Care will be taken to obtain multiple, repeatable measurements of permeability in the region where the long-term packer will be installed. Storage properties will likely not be interpretable when using gas as a working fluid. Although unlikely, high gas permeability in the interval of the gas circulation system could impact our ability to interpret results from the test.

The apparent gas permeability with depth will be used to quantify and confirm the extent of the access drift DRZ. It is expected the majority of the drift DRZ will extend to no more than 5 ft from the drift opening along the borehole, because the N-940 access drift was excavated recently in 2013, and it has small dimensions compared to other WIPP drifts (i.e., approximately 16.5 ft [5 m] wide by 13.5 ft [4.1 m] high, less 2 ft [0.6 m] of run-of-mine fill added to the floor to drill the upper boreholes). This confirmatory testing will provide a measure of the pre-test apparent gas permeability distribution along the borehole that will be useful for numerical modeling, comparison of pre- and post-test permeability, and ensure the packers provide a good seal against mine ventilation. If borehole conditions allow, the permeability will be measured again after heating (Section 4.1) to quantify any changes along the length of the borehole due to borehole closure, brine migration, and creep closure.

The packers that will be installed long-term, during the heated test, will have to account for impact of temperature. Packer inflation pressure is temperature dependent. The inflation pressure will be checked—and if necessary modified—once the heater is on and the test interval has heated up.

2.4 Grouting of Instruments into Horizontal Boreholes

The sensors installed in the 1.75-in [4.4 cm] diameter thermocouple (T), electrical resistivity tomography (E), and fiber-optic distributed sensing boreholes (F) will be grouted into place. Grout (Table 3) will be pumped down the inside of a ¾-in [1.9 cm] flush-joint polyvinyl chloride (PVC) conveyance pipe, which will have the sensors attached to the pipe (inside or outside the conveyance pipe). The grout will flow back towards the drift face along the outer annulus.

Table 3. Grout for instrument boreholes

Material	Amount by weight
Cement	49.5 %
Attapulgate	5 %
Run-of-mine salt	12.5 %
Water	33 %

Centralizers (additively manufactured plastic spacers) will be added to the outside of the conveyance pipe to help ensure a uniform grout annulus, reducing air bubbles between the sensors and borehole wall. A collar (i.e., annular ring) will be attached to the outside of the ¾-in [1.9 cm] PVC conveyance pipe near the drift wall to prevent the grout from flowing out into the drift and to apply some back-pressure to get the grout to better fill the annulus. The ¾-in [1.9 cm] PVC conveyance and grouting pipe will include a ball valve left in place to prevent grout from flowing out of the tube after removing the grout pump (i.e., after grouting, but before the grout sets).

For boreholes longer than a single 10-ft [3 m] joint of PVC pipe, flush-joint PVC pipe will be used to minimize grout plugging in the annulus at joints. If needed, small holes may be added along the length of the PVC to allow cement to flow out at multiple locations, in case there is blockage or resistance during grout injection. The rough amount of grout expected to be used (i.e., based on length and diameter of the borehole) and the amount actually used will be documented and compared. This is mainly as an additional check to see if large amounts of air (too little grout) or flow into intersecting fractures (too much grout) exists.

2.5 Heater Test, N₂ Circulation, and Tracer Addition Sequence

Following permeability testing of the 2.1-in [5.3 cm] and 4.8-in [12.2 cm] diameter boreholes, the long-term HP borehole packers will be installed; the AE sensors will be inserted into their boreholes on centralizers; the T, E, and F sensors will be grouted into their boreholes; and finally the flow of dry N₂ gas will be initiated through the central (HP) borehole plumbing. The smaller-diameter 1.75-in [4.4 cm] boreholes cannot be packer tested for permeability, so instrumentation can be installed in them via grouting after drilling is complete (i.e., grouting doesn't need to wait for permeability testing).

Two initial tests will be conducted at each array at the same time. As part of the first test, 1 month of background data, associated with flowing N₂ and measuring geophysical properties, will be collected before turning on the heater. One additional month of data will be collected after turning on the heaters, before adding the gas tracers to the D borehole, to observe the natural tracer response (e.g., geogenic gases and natural water vapor) of the salt to heating. We hope to observe any difference in gases produced by the salt due to heating before adding gas tracers. Gas samples will be collected from the drift air in Mylar (biaxially-oriented polyethylene tetraphthalate) bags to check for evidence of tracer gas leakage into the access drift.

The first test will be heated for ~6 months (to allow the flow system to approach a steady-state during heating), followed by a cool-down period of up to two months (to allow any thermal over-pressurization

to decay away). Once the system is cooled down, liquid tracers will be added to the source (D) borehole, before turning on the heater. The heater will be turned back on for ~6 months to observe the response of the system with the liquid tracers added.

Both the gas and liquid tracers will be added to the unheated test at approximately the same time they are added to the heated test, to maximize the comparability of the observed responses in the heated and unheated tests.

3. Configuration of Boreholes and Measurement Type

This section presents the description of individual testing boreholes and the sensors in each.

3.1 HP (Heater and Packer) Borehole

There will be one central 12-ft [3.7 m] long (4.8-in [12.2 cm] diameter) HP borehole in each array (Figure 2). The 750-Watt quartz lamp heater and centralized borehole-closure gage will be mounted behind the 4.5-in [11.4 cm] diameter 2-ft [0.61 m] long Aardvark packer via a pass-through 1-in [2.5 cm] steel pipe. The packer will be set approximately 5-ft [1.5 m] deep into the borehole (final depth to be confirmed by results of gas permeability testing—see Section 2.3). There will be two ¼-in [0.6 cm] stainless-steel gas lines passing through the packer: one connected to ultra-high purity (UHP – 99.999%) bottled N₂ (inflow) and the other connected to the downstream gas instrumentation (outflow).

3.1.1 Handling and Analysis of Gas Streams

The downstream gas instrumentation will be comprised of a Picarro cavity ring-down spectrometer (CRDS) and Stanford Research Systems (SRS) gas analyzer on one branch, and the LI-COR gas analyzer on the other branch. The outputs of two gas analyzer branches will be fed back through Drierite desiccant canisters. The Drierite desiccant will be weighed weekly to confirm the cumulative mass of water leaving the system. Solenoid-actuated valves upstream and downstream of the gas analyzers will allow switching of the gas streams between instruments under the control of a Campbell Scientific CR1000X datalogger. Figure 3 shows the flow of gases from the two HP boreholes through the gas analyzers and Drierite desiccant.

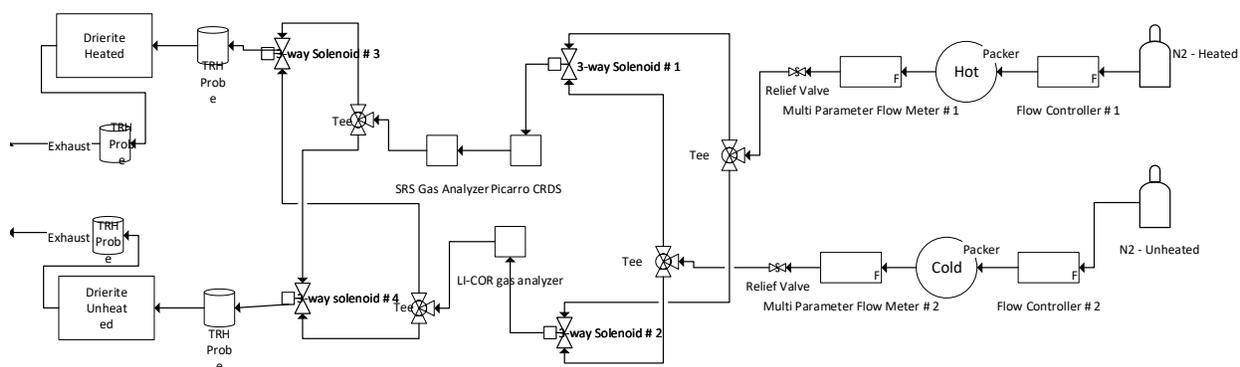


Figure 3. Plumbing of gas flow from HP boreholes through Picarro, SRS, and LI-COR analyzers.

Upstream of each HP borehole, a bottle of UHP N₂ will be flowing at a constant flowrate (via a flow controller). Based on the results of the shakedown test, the test will be run at a target flowrate of 200 mL/min at standard temperature and pressure (STP). This flowrate can be adjusted up or down based on the observed brine flow into the test interval, and to test if there is a dependence of the observed water inflow rate on the gas inflow rate (previous WIPP heater test indicated there was not; Nowak & McTigue, 1987).

The mass flowrate of gas (reported at STP or reported with temperature and pressure for correction) will be monitored both upstream and downstream of the packer to confirm the mass balance of N₂ flowing through the system as an indication of any leaks of the packer-isolated interval through time. Downstream of the flowmeter after the packer, there will be a pressure relief valve and a pair of plumbing tees and three-way solenoid valves to allow switching the gas streams from the two boreholes between the two branches of gas analyzers instruments (Figure 3).

The Picarro CRDS, LI-COR, and SRS gas analyzers will be shared between the two borehole tests (heated and unheated). The gas plumbing will be switched between the Picarro/SRS branch and the LI-COR branch periodically via solenoid-actuated three-way valves. The Picarro analyzer reports the concentration of specific water isotopes in the gas stream (stable oxygen and hydrogen isotopes), while the LI-COR analyzer reports mmol/mol H₂O and μmol/mol CO₂. The analog outputs from the LI-COR will be connected to a Campbell Scientific CR1000X datalogger, while the Picarro and SRS gas analyzers have their own logging computers.

The SRS gas analyzer is a quadrupole mass spectrometer designed for atmospheric pressure inlet pressures. Before tracer gas is added to the D borehole, a suite of gases related to possible geogenic sources will be monitored. Just before adding the gas tracers, the SRS analyzer will be switched over to monitor a suite of gases, including the added tracers.

Before adding gas tracers (and continuing through the initial activation of the heater), we will monitor a suite of possibly enriched geogenic gases including isotopes of He [atomic mass 4], Ne [20, 21, and 22], Ar [36 and 40], Kr [84] and Xe [132] (Ballentine & Burnard, 2002). Out of these gases, ⁴He will continue to be monitored after adding the tracer, as it is not being added to the source borehole (D), while Kr, Xe, and Ne will be added to the D borehole.

One day before adding the gas tracers to the D borehole, the suite of monitored gases will be changed to observe background data. The gases to monitor after tracer addition include the primary isotope of the introduced tracer noble gases Ne [20], Kr [84], and Xe [132] will be monitored along with the primary electron fragment of SF₆ [127]. CO₂ [44] will be monitored to compare against the data provided by the LI-COR 850 instrument. Cl [35] will be monitored to assess mechanisms for production of chlorine and hydrochloric acid gas from heating the salt and brine in the borehole (Kuhlman et al., 2017). N₂ [29] (isotopologue is ~0.8% of atmospheric N₂) will be monitored to normalize the response of the instrument against variations in gas flow rate and instrument sensitivity (i.e., the gas stream will mostly be N₂). O₂ [34] (isotopologue is ~0.4% of atmospheric O₂) will be monitored to quantify the contribution of mine ventilation to the gas stream, since no processes in the borehole should generate O₂. Since only lower-concentration isotopes of N₂ and O₂ will be monitored with the other lower-concentration tracer gases, the more sensitive electron multiplier can be used without saturating the detector. At the beginning of the test (before turning on the heater), a single day of added tracer background data will also be recorded. Along with the comparison between the heated and unheated arrays, these additional background data will be used to quantify if there is a change in background between heated and unheated conditions.

The output streams from the gas analyzers go through another pair of plumbing tees and three-way solenoid-actuated valves before passing through a pair of temperature and relative humidity (RH) probes and a canister of Drierite desiccant. The RH probes before and after the desiccant will confirm the RH of the gas stream. The final set of switching valves ensures that one set of Drierite canisters is always associated with the heated array, and one is always associated with the unheated array, even though the intervening gas analyzers are switching between arrays.

3.1.2 Heater Power

The 750-Watt quartz lamp infrared heater will be mounted on the end of the 1-in [2.5 cm] steel pipe with disc-shaped reflectors perpendicular to the 1-in [2.5 cm] pipe installed on either end of the heater to confine the radiative energy to approximately an 18-in [45.7 cm] long interval of the borehole wall. Two

thermocouples will be installed, against the borehole wall (attached to the reflectors), between the borehole closure gage and the heater. The heater will be controlled by a Watlow controller set at a constant temperature of 120°C (based on experience in the shakedown test this should be require approximately 80 to 90% of the rated power for the heater element), while a thermocouple near the borehole closure electronics will be used as an emergency over-limit check, shutting down heater power in case some malfunction leads to shorting or overheating. The Watlow controller output (applied power, current, and voltage through time) will be transmitted to a Campbell Scientific CR1000X datalogger. The hot and neutral wires for the heater will pass through the packer in a Conax fitting, while the ground wire for the power will be connected to the 1-in [2.5 cm] conveyance pipe with a brass screw clamp.

The unheated array will not have a heater, heater controller, or reflectors.

3.1.3 Borehole Closure

The borehole closure gage will be a four-arm spring steel centralizer fixed to the 1-in [2.5 cm] pipe on one end, with the other end connected to a polyetheretherketone (PEEK) slider, sliding on a notch over the 1-in [2.5 cm] pipe. The slider connects to an axial linear variable differential transformer (LVDT), which measures displacement of the slider. Displacement can be related linearly to borehole circumference. The response of the LVDT at different borehole radii will be measured in the lab for calibration of the output.

Strain gages are also attached to each of the four centralizer arms, to allow confirmation of directionality in closure, and to serve as a backup measure of borehole closure. The LVDT is equipped with an in-line signal conditioner. The LVDT and the strain gages will be connected to a Campbell Scientific CR1000X datalogger.

3.1.4 Sealing Pass-through Wires

The two power supply wires for the heater (heated array only), LVDT, four strain gages, and four thermocouples will go through the 1-in [2.5 cm] steel pipe and will be sealed at the drift face using Conax fittings. The 1-in [2.5 cm] pipe will be terminated in a stainless-steel plumbing tee. Each of the two sides of this first tee will have another tee (Two ½-in [1.3 cm] fittings on a tee on one side and two ¼-in [0.6 cm] fittings on the other tee). Each of these four tee ends will have a Conax fitting for a single type of wire (see Figure 4).

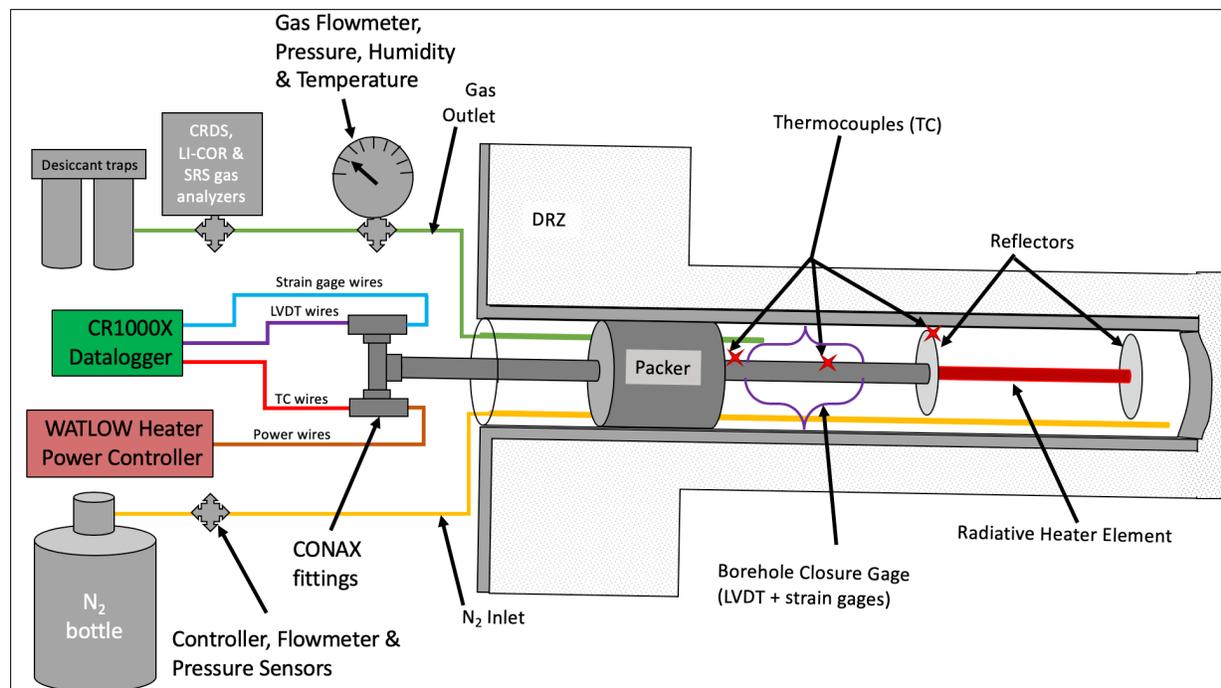


Figure 4. Wiring and plumbing diagram for the heated HP borehole

3.2 AE (Acoustic Emissions) Boreholes

There will be three 9-ft [2.7 m] long (2.1-in [5.3 cm] diameter) AE boreholes (Figure 2) with initially eight piezoelectric sensors in each borehole (the 24 sensors will be moved between the heated and unheated array, but will mostly be on the heated array). The AE boreholes will not be grouted. Of the 24 sensors, 16 channels will be used to listen for AE events and triangulate the origin of individual acoustic emission events, while the other eight channels will be used as wave sources. The 16-channel Mistras data acquisition system and sensors will be used to monitor the heated borehole most of the time to capture AE generated during heat-up and cool-down. For comparison, the system will occasionally be used to monitor the unheated array, to get an estimate of the unheated background noise. There will be thermocouples in contact with the borehole wall by each centralized piezoelectric sensor (i.e., also eight per borehole). The thermocouples and piezoelectric sensors will be located on separate centralizers. The three AE boreholes are arranged in a triangle surrounding the heated borehole.

The AE sensors are installed on the arms of Quick-ZIP centralizers (made of polyoxymethylene plastic; POM) on the outside of a 3/4-in [1.9 cm] stainless-steel hollow-tube conveyance. The faces of the piezoelectric transducers will be glued to half-spherical balls, which act as wave guides to ensure good contact between the transducers and the borehole wall. The piezoelectric transducers will be oriented to be on the arm of the centralizers closest to the HP borehole to optimize detection of the first arrival (i.e., P-wave) of acoustic emissions from the heated borehole and ultrasonic pings from other sensors. The Mistras system will automatically pick AE events based on a magnitude threshold, but the system also records the full stream of digitized data, which will be analyzed and post-processed elsewhere.

Multiple times during the test (e.g., at least two times before, two times during, and two times after heating) the eight piezoelectric sensors not connected to the Mistras system for AE observation will be excited with a square wave “ping,” while the other 16 sensors are listening to measure ultrasonic wave travel time between sensors (i.e., ultrasound travel-time tomography). This requires an external square wave generator since the system configuration only allows for one source channel. The ultrasound travel-time tomography test will also be conducted in the unheated array for comparison against the heated

array. If at any time the AE boreholes do not have sensors in them, they will be plugged to prevent dry out.

The piezoelectric sensors have 9.8-ft [3 m] leads, which are attached to an in-line signal conditioner box at the drift face. The cable from the signal conditioner to the Mistras control computer does not have the same cable-length constraints. The Mistras logging system with 16 channels is a CPU with a monitor, keyboard, and mouse installed inside a NEMA enclosure.

3.3 T (Thermocouple) Boreholes

There will be two 18-ft [5.5 m] long (1.75-in [4.4 cm] diameter) T boreholes (Figure 2) with 16 thermocouples in each (grouted outside $\frac{3}{4}$ -in [1.9 cm] PVC conveyance pipes—see Section 2.4). One of the boreholes will be at 24 in [61 cm] radial distance away from the edge of the heated borehole (T2), and the other at 36 in [91 cm] radial distance (T1). Thermocouples will also be located in other measurement boreholes to increase the density of observations and help correct other observations for local temperatures. The thermocouples will be read on Campbell Scientific CR1000X loggers.

3.4 E (Electrical Resistivity Tomography) Boreholes

There will be three 18-ft [5.5 m] (1.75-in [4.4 cm] diameter) E boreholes (Figure 2) with 16 electrical resistivity tomography (ERT) electrodes (12-in [30 cm] spacing between adjacent electrodes) in each, grouted outside $\frac{3}{4}$ -in [1.9 cm] PVC conveyance pipes (Section 2.4). The electrodes will be driven by Multi-Phase Technologies ERT controller (MPT DAS-1), located in a NEMA enclosure in the drift. Combining the heated and unheated arrays, there will be total of six ERT boreholes with a total of 96 electrodes. Because the DAS-1 system only has 64 electrode positions, an additional multiplexing unit (MPT-MUX) with an additional 64 electrodes will be added. The ERT controller and electrodes were tested in borehole at WIPP as part of the shakedown testing. Five thermocouples will also be grouted in place with the ERT electrodes for each borehole. Based on shakedown test experience, the thermocouples are known to read anomalously high temperatures during ERT surveys (i.e., when applying current to ERT electrodes) when located in the same boreholes as the ERT electrodes.

A complete ERT survey takes <1 hour to perform for each array. They will be conducted multiple times during the test (i.e., every-other week before, during, and after heating) to measure the temporal evolution of the apparent resistivity distribution. The unheated array will be surveyed at approximately the same times as tests are performed on the heated array, to promote comparability between tests.

Apparent resistivity is a function of the salt temperature, brine content and porosity. Metal components, the presence of salt grout, and any ground control near the test arrays will impact the apparent resistivity, but these components should be fixed through time. The analysis will primarily look at the time evolution of apparent resistivity.

The ERT system will be operated only by personnel trained in WIPP electrical safety.

3.5 F (Fiber Optic Distributed Sensing) Boreholes

There will be one 18-ft [5.5 m] (1.75-in [4.4 cm] diameter) F1 borehole and a second 30-ft [9.1 m] F2 borehole (Figure 2), both with grouted fiber-optic distributed sensors. The shorter F borehole will have one fiber (distributed temperature sensing [DTS]), while the longer borehole will have two (DTS and distributed strain [DSS] sensing). The strain fibers will be attached to the outside of $\frac{3}{4}$ -in [1.9 cm] PVC conveyance pipe and grouted into the borehole (see Section 2.4), with four thermocouples also grouted in with the sensors for calibration and verification. The straight DSS fiber will measure longitudinal strain along its length. The DTS fibers will be housed in small-diameter (0.04 in [1 mm]) plastic tubes before attaching to the PVC conveyance pipe and will measure temperature along the length of the fibers. For high accuracy (0.1°C) temperature measurements, a reference temperature (i.e., a water bath) will be set

up. The DTS measurements can be validated or calibrated against thermocouple observations in the same borehole.

The fibers will be connected to Luna DSS and DTS receivers (IDiSi 6102 and IDiSi 6104), located in a NEMA enclosure in the drift. The thermocouples will be read using a Campbell Scientific CR1000X datalogger.

3.6 D (Tracer Source) borehole

There will be one 15-ft [4.6 m] (2.1-in [5.3 cm] diameter) D borehole (Figure 2) with an 18-in [46 cm] long 1.9-in [4.8 cm] diameter long-term packer inflated in the borehole. The tracer borehole and packer will have two different configurations for gas and liquid tracer testing. For gas tracer testing, the packer will be set at a depth of approximately 5 ft [1.5 m] into the borehole (depth to be confirmed by permeability testing—see Section 2.3). For liquid tracer testing, the packer will be set within 2 ft [61 cm] of the back of the borehole (approximately 10.5-ft [3.2 m] depth). The borehole gas tracer test will be conducted first, then the liquid tracer test will be conducted second (Section 2.5).

3.6.1 Gas Tracers

To add the gas tracers, the 1.9 in [4.8 cm] packer will be set at approximately 5-ft [1.5 m] depth (depth to be confirmed by permeability testing—see Section 2.3). Teflon tubing will be connected to a packer pass-through, to bring it to the drift face, and the gas tracer mixture will be added to the tubing. UHP nitrogen gas will be added until the gas pressure behind the packer is pressurized to 5 psi gage [34 kPa], then it will be shut in. The pressure of the gas tracer will be monitored while it decays, as in a pressure-decay permeability test. However, if high permeability in the gas tracer borehole (D) is found, this part of the experiment will need to be revised.

The gas tracers will be a mixture of noble gases (Ne, Kr, and Xe) with SF₆, that will be added to the air behind the packer. Helium will not be added as a tracer, to better allow characterization of any natural (i.e., geogenic) release of ⁴He from the salt due to heating and damage accumulation (Bauer et al., 2019). Argon will not be added as a tracer or monitored, because of its relatively high concentration in the atmosphere (~1%).

An inline SRS gas analyzer (attached to HP borehole—see Section 3.1.1) will report real-time relative concentrations of up to 10 gases (including CO₂, Cl, O₂, N₂, He, Ne, Kr, Xe, SF₆). The gas stream will also be sampled every two weeks in a Mylar bag from the central HP borehole. These bag samples will be analyzed in a laboratory with a gas chromatograph to confirm and calibrate observations of gas composition by the SRS analyzer.

3.6.2 Liquid Tracers

For the liquid tracers the 1.9-in [4.8 cm] packer will be set to create a 3-ft [91 cm] long interval behind the packer by placing the packer at approximately 10.5-ft [3.2 m] depth (Teflon tubing will be connected to the packer pass-throughs to bring them to the drift face). The liquid tracers will be added to one of the pass-throughs with a pump. Up to one liter of synthetic WIPP brine with liquid-phase tracers (below) will be added to the back of each tracer borehole using the lower elevation pass-through. The brine (Table 4) will be similar to the G-weep brine (GWB) recipe (Xiong, 2008), and was formulated from an average of samples from horizontal boreholes in WIPP completed in Map-Unit 0 (MU-0) (Kuhlman et al., 2018). The resulting brine should have ion compositions listed in Table 5.

The upper pass-through will be left open to allow gas to escape from the interval while filling with brine. Once the interval will not take more brine without flowing out, the upper pass-through will be capped off and the head space in the packer interval will be pressurized to 5 psi gage [34 kPa] with N₂. The added gas pressure will be monitored in time (like a pressure-decay test), then the pass-through will be capped off.

Table 4. Liquid tracer recipe (g salt/L solution)

Salt	GWB (Xiong, 2008)	MU-0 brine
NaCl	179.61	177.08
KCl	34.84	29.45
LiCl	0.19	0.21
Na ₂ B ₄ O ₇ ·10(H ₂ O)	15.06	12.91
CaCl ₂ ·2(H ₂ O)	2.03	1.04
NaBr	2.74	1.96
MgCl ₂ ·6(H ₂ O)	207.05	180.44
Na ₂ SO ₄	25.23	24.02

Table 5. Liquid tracer ionic compositions (Kuhlman et al., 2018)

Ion	Cl ⁻	Br ⁻	SO ₄ ⁻	Na ⁺	K ⁺	Mg ⁺⁺	Ca ⁺⁺	Li ⁺	B(OH) ₃
Brine [g/L]	186	1.5	17	84	14	23	0.28	0.04	1.5

The synthetic WIPP brine liquid tracers will include:

- Water with a lighter stable-water isotopic signature than Salado brine, from a high-elevation snow source, will be used to make the synthetic brine. The stable-water isotopic signature of completed tracer will be measured, since the isotopic makeup of hydrous salts used to make the brine is uncontrolled by the manufacturer.
- An organic fluorescent tracer, Na-naphthionate (also known as 1-Naththylamine-4-sulfonic acid sodium salt hydrate), which fluoresces at 325 nm (violet/blue) will be added at a concentration of 2 mmol. This tracer has been identified as minimally sorbing in high-saline environments (Magal et al., 2008). Fluorescent tracers are detectable in the laboratory using a fluorescent spectrometer at very low levels. A “black light” flash light will be used in the field to observe the presence of the tracer during sampling and post-test coring operations. Na-naphthionate is light sensitive, so the tracer and any collected liquid brine samples for spectrometer analyses will be stored in amber bottles.
- An anionic tracer, sodium perrhenate (NaReO₄) will also be added at a concentration of 10 mmol. It is an anionic form of rhenium, soluble in brine and detectable at very low concentrations using a mass or optical emission spectrometer. Since it is anionic, it should act as a conservative tracer.

The prepared liquid tracer will be fully characterized for the isotopic and dissolved makeup before adding to the system. The stable-water isotope makeup of water flowing into the HP borehole will be monitored via the Picarro CRDS attached to the exiting gas stream (Section 3.1.1). The composition of the brine collected in the liquid sampling borehole will be sampled weekly and monitored for perrhenate and fluorescent dye. Liquid samples can also have their stable water isotopic makeup measured in the laboratory. After the test is complete, the salt between the source and central boreholes will be cored and sampled. Black lights will be used to characterize the distribution of Na-naphthionate in the salt during follow-up post-test coring.

3.7 SM (Liquid Sample) Borehole

A 15-ft [4.6 m] (2.1-in [5.3 cm] diameter) liquid sampling borehole (SM—see Figure 2) will be plugged beyond any large fractures near the drift wall with a sewer plug (or similar device). The plug will have a Campbell Scientific EE181-L or equivalent sensor to measure air temperature and relative humidity (RH) behind it to confirm equilibrium with formation brine (~75% RH) behind the plug. This RH indicates there is not significant mine ventilation into the borehole, which would remove liquid water. The RH and temperature sensor will be logged using a Campbell Scientific CR1000X datalogger.

Through the pass-through in the plug, a ¼-in [0.6 cm] Hastelloy tube will be run to the back of the borehole. The tube will be sealed into the plug pass-through with silicone. At most times, the tube will be capped at the drift face.

Weekly, the cap from the ¼-in [0.6 cm] Hastelloy tube will be removed to collect a liquid-phase sample from the back of the borehole. A Nalgene polypropylene fluid-transfer closure will be used to connect a portable vacuum pump to the permanent ¼-in [0.6 cm] Hastelloy tube. The closure will be connected to a larger (1 L) Nalgene sample bottle. This larger Nalgene sample bottle will be used to fill smaller sample bottles, including an amber container (with minimal head space) for fluorescent tracer analysis in the lab (black light will be used to check for fluorescence in the field). After filling the smaller sample bottles, the remainder of the brine produced from the borehole with the vacuum pump will be collected into larger Nalgene bottles. The total mass of brine collected will be estimated and recorded. The same vacuum pump can be used at both the heated and unheated arrays, but dedicated Hastelloy tubing and fluid-transfer closures will be used (one for each borehole). Fluid-transfer closures will be rinsed off between sampling events with deionized water. New sample bottles will be used for each sampling episode.

3.8 SL (Seal) Borehole

The 8-ft [2.4 m] (4.8-in [12.2 cm] diameter) SL borehole (Figure 2) will have a lab-constructed cement seal emplaced. The cement seal will have a rosette of three perpendicular Geokon vibrating wire strain gages and thermistors, and a backup VPG concrete embedment gage that only reads a single component of strain. These sensors will be installed in a cement plug in the laboratory, and that plug will be installed in the SL borehole to form a seal when the salt closes in around it. The plugs with their strain gages will be made to fit snugly (~4.6-in [11.7 cm] diameter) into the horizontal boreholes. The seals will be pushed to the back of the seal borehole, and a sewer plug (or similar device) will be used to seal the borehole near the drift (allowing the strain gage wires through) from excessive mine ventilation. A hygrometer (Campbell Scientific EE181-L or equivalent) will be installed just behind the plug to monitor the RH and temperature of the air, confirming the isolation of the interval from mine ventilation (i.e., maintenance of 75% RH). The RH and air temperature sensor wire, along with the strain gage wires, will feed through the pass-through on the plug, and be sealed with silicone.

The strain gages in the cement plugs serve two purposes. First, they will provide information regarding when the borehole creeps in around the cement plug, causing the cement plug to deform. Secondly, once the salt has made contact and loaded with the plug, the three-dimensional strain in the cement plug will provide information on the three-dimensional stress state in the rock (i.e., the stress-strain behavior of the cement plug is assumed to be well-known).

The strain gages and thermistors (three perpendicular Geokon 4242X vibrating wire strain gages—including their thermistors—and a VPG EGP-5-120 embedment gage), and hygrometer will be monitored with a Campbell Scientific CR1000X datalogger. The vibrating wire strain gages will be connected a Campbell Scientific AVW-200 vibrating wire strain gage reader through an AM16-32B Campbell Scientific multiplexer before being connected to the CR1000X. The seals will be monitored until they are cored to test the cement/salt interface after the test is complete. These seals will be left in place for an extended period of time (i.e., several months to years) after the primary heater and tracer test is complete in the HP boreholes, to allow the plugs, brine, and salt to interact.

3.9 Drift (non-borehole) Observations

Ambient drift air pressure, air temperature, ventilation (i.e., “wind”) velocity, and relative humidity will be monitored at a high frequency in the drift near the location of the boreholes. The drift weather station will have its own datalogger. Temperature will be monitored on the drift wall, to quantify how the heat from the test interacts with the drift air. The drift thermocouple will be monitored by a Campbell Scientific CR1000X datalogger. A thermal imaging camera will also be used to document the temperature distribution on the drift wall near the heated borehole (including the location around the drift thermocouple measurement) and document any leaks or hot spots in the drift during heating.

Immediately before and after the gas tracer introduction (Section 3.6.1), grab samples of air from the drift will be collected in Mylar bags for gas compositional analysis, to discern if tracer gas is leaking into the access drifts.

4. Post-Test Samples and Analyses

Pre-test activities, test data collection, and sampling (during heating and cooling sequences associated with gas and liquid tracer monitoring) are described in the previous sections. This section discusses the proposed post-test sampling and analyses (after cool-down). These descriptions are preliminary as some of the analyses depend on removal of packers or other equipment from boreholes, which could be prevented by borehole creep closure.

4.1 Post-Test Gas Permeability Testing

Depending on the ability to remove the N₂ circulation packer from the HP borehole and to insert the gas-testing packers into this and other boreholes, a second round of gas permeability packer testing will be conducted in the 4.8-in [12.2 cm] (HP) and 2.1-in [5.3 cm] diameter (D and SM) boreholes. Pre-test packer permeability testing is described in Section 2.3. Post-test permeability characterization will be used to quantify the changes in apparent gas permeability and damage along the length of these three boreholes (the SL borehole will not be available, since the seal experiment will still be running).

4.2 Post-Test Over-Core

If the heater and packer can be removed safely from the HP borehole after the test, a large-diameter (~12-in [30 cm]) horizontal core will be collected across the heated region (i.e., the region between the HP, D, and SM boreholes—see Figure 5) to quantify the effects of heating and the spatially map distribution of liquid tracers in the salt. Similar core will be collected in the unheated array, for comparison of tracer movement between heated and unheated arrays. If the heater cannot be removed, smaller cores will be collected from the area between the HP, D, and SM boreholes. The SL test will also be over-cored at a later date (Section 5.13).

To reduce damage to the salt near the boreholes during the over-coring process, the boreholes could first be partially filled with epoxy, cement, or some other stabilizing sealant—epoxy was extensively used in over-coring work in bentonite by Mäder et al. (2016).

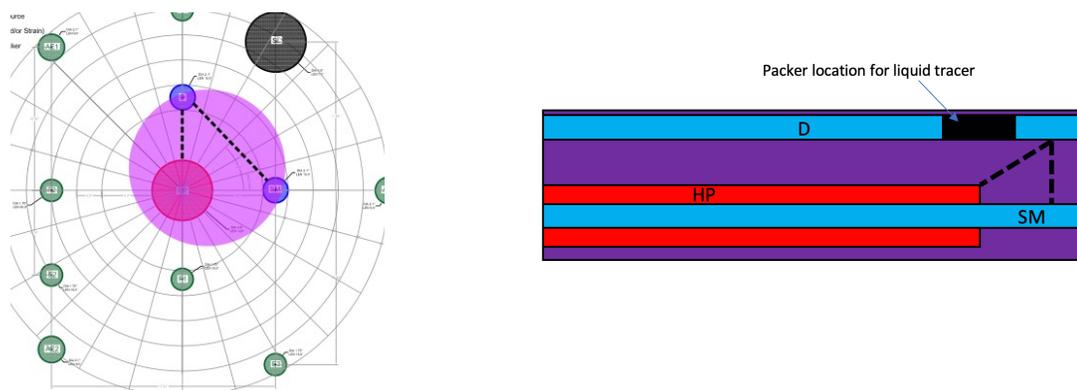


Figure 5. Post-test 12-in [30 cm] diameter over-core location (large purple circle). Drift view (left) and side view (right). Possible sub-sample transects for analyses indicated with black dashed line.

Any core collected after the test in the region where tracers were added will be checked for fluorescent tracer by ultraviolet flashlight and will be preserved in a similar manner to the way the pre-test core was collected and preserved. This core will also be sent to NETL for CT imaging and documentation. The borehole from over-coring should also be documented with borehole logging, using a black-light light source.

The ERT, DSS, DTS, and AE sensors will be disconnected before drilling the post-test core. It may be of technical value, if feasible, to continue these observations during the post-test drilling. If successful, the results could quantify the sensitivity of geophysical methods to damage or other changes induced by coring operations. The ERT survey may be difficult to conduct with drilling equipment present due to standoff distances and other electrical safety requirements. The strain, temperature, and humidity measurements in the SL borehole will continue if possible, or at least be re-connected after coring is complete.

After both pre-test and post-test cores have been analyzed via non-destructive whole-core methods, the cores will be sub-cored and sampled for laboratory microscopic (e.g., thin section petrography) and compositional analyses.

5. Plan for Data Interpretation

The components of the field test and associated data types to be collected, presented in the previous sections, are discussed in this section with regard to how the data may be interpreted. High-level summary of the data types and interpretation goals are given in Table 2. The following descriptions and interpretation plans are preliminary because the data and samples have not been collected yet. They constitute a tentative plan for additions to the technical baseline for disposal of heat-generating radioactive waste in salt. Other uses may come about after the data and samples are collected, including applications or limitations not foreseen.

In the following sections, the phrase “time series” is used to indicate a high-frequency dataset recorded automatically (e.g., thermocouple-based temperature observations recorded every few seconds), while the phrase “test results” is used to indicate a test or analysis done periodically (at least twice), but requiring manual operation or intervention (e.g., ERT, ultrasound travel-time tomography, borehole permeability testing, or liquid brine sample collection). The phrase “analysis” is used to indicate something conducted once (e.g., destructive core analyses).

5.1 Uncertainty Analysis

Uncertainty associated with the observations or instruments themselves will be estimated quantitatively and presented with the data. It is expected that such measurement uncertainty will be a minor part of the overall uncertainty associated with interpretation.

Analysis of data collected as part of the test will require fitting observations to analytical and numerical models. Two other types of uncertainty will be evaluated: 1) uncertainty associated with the structure of the models (i.e., is the correct physics included), and 2) uncertainty associated with parameter values used in the models. Different models may be used to fit the same data, and each type of model may have different complexity and epistemic model uncertainty. To the extent possible uncertainty in model results and interpretations based on them will be addressed explicitly. Modeling assumptions and other information (e.g., files and software) will be developed sufficiently to allow other researchers to replicate the results.

The BATS field test has been proposed as one of the tasks for the next round of the Development of Coupled Models and their Validation Against Experiments (DECOVALEX) international model benchmarking exercise (from 2020-2023). Sharing of data, background, interpretations, and model input files will be a natural part of this exercise. We will need to explicitly assess and discuss uncertainty to support the process.

5.2 Interpretation of Data Using Numerical Models

Given the nature of the test (i.e., geometry and coupled processes), it will likely not be possible to interpret all the data from the test using only analytical solutions, hand calculations, spreadsheets, or other simplified tools. To interpret some aspects of the test will require development of gridded numerical simulations. Results from these numerical models will then be compared to test observations, and adjustments made to improve the agreement between the models and the test data. This tuning process should achieve several goals: 1) evaluation of the conceptual models (i.e., whether the most important processes are included); 2) verification of numerical models (i.e., whether the mathematical models are being solved appropriately); and 3) better design for future field tests (i.e., what test conditions should be used, and which data collected, to validate predictive models). When possible, all aspects of the tuning process should explicitly incorporate uncertainty quantification.

In the field test, there are multiple coupled fundamental thermal, hydrologic, mechanical, and chemical processes occurring. Temperature is known to have significant effects on hydrologic, mechanical, and chemical processes. Mechanical damage influences the distribution of moisture, and chemical processes. Observed trends in seismic propagation, electrical conduction, isotope fractionation, mineral precipitation,

and RH (water activity) will be influenced by changes in temperature, mechanical state, and aqueous chemistry. Interpretation of test data will help to determine which couplings are mainly “one-way” (e.g., thermal influence on other processes) and which exhibit stronger “two-way” feedback (e.g., mechanical-hydrologic-chemical).

5.2.1 Thermal Models

Within the host salt conduction is probably the primary means of heat transfer regardless of saturation state. In open spaces (such as the HP borehole) gas-phase natural or “free” convection and radiation may also be important. Convective heat transfer may also occur where there is sufficient gas permeability and gradients of temperature (or pressure).

Heat conduction alone is probably a good approximation for heat transfer from the wall of the HP borehole to the far field. Boundary conditions, particularly at the access drift wall (i.e., perpendicular to the boreholes) may have significant influence on the observed transient thermal behavior (Stauffer et al., 2019). The source condition may be approximated numerically by a constant-temperature surface or a constant energy flux. The energy input to the salt will be determined by the power applied by the heater controller, and the model source conditions will be directly related to observations. We note that thermal conductivity for intact salt and crushed salt has been characterized as temperature-dependent (e.g., Bechthold et al., 2004).

Two-phase flow of gas and liquid through the porous medium will be incorporated to consider the boiling of brine and transport of vapor (and enthalpy) away from the heater. If liquid brine returns driven by a capillary gradient or gravity, the heat-pipe phenomenon could produce significant changes in near-field porosity (mechanical) and mineralization (chemical). Two-phase flow and storage properties of the salt are needed to assess boiling behavior and the potential for heat-pipe activity (i.e., the capillary pressure and relative permeability as functions of saturation or water content; Johnson et al., 2019).

Temperature time series from locations throughout the salt will be used with observations of the temperature in the access drift and power input at the heater to constrain the predictions of temperature distribution in the salt.

5.2.2 Mechanical Models

The mechanical behavior of salt is elastic on short time scales, and exhibits both brittle and plastic responses (i.e., dilatancy damage, and creep consolidation of openings with healing). Mechanical behavior is strongly influenced by elevated temperature (e.g., decreased stiffness, and accelerated creep strain rate). Thermal expansion or contraction of salt and brine can impact the stress state. Mechanical behavior of salt, including that around boreholes, likely has only a small impact on thermal properties and temperature distribution (i.e., one-way coupling). Mechanical behavior can be used to predict changes in hydrologic properties (i.e., volume strain can be related to permeability; Rutqvist et al., 2018).

Mechanical models can be used to predict the borehole closure observed in the HP and SL boreholes. Observations in the HP borehole will provide borehole closure information (changes in circumference) during the entire test, while the SL borehole will have three-component strain sensors embedded in cement plugs that deform once salt creep has made contact. The F2 borehole will have the longitudinal component of strain observed along the length of the 30-ft [9.1 m] DSS fiber.

Depending on constitutive behaviors, primary hydrological transport properties (i.e., porosity and permeability) of the salt could be changed by damage accumulation from heating and cooling. The distribution of damage (i.e., volume strain or changes in porosity) will be investigated using ERT and ultrasound travel-time tomography results (which jointly could discern dilatancy from dry out effects).

5.2.3 Hydrologic Models

Transport of gas and liquid brine through the salt may be strongly coupled to the temperature distribution. Thermal expansion increases the liquid pressure and can drive brine flow, with mechanically significant pressurization if the liquid permeability is low enough. The ultimate expression of hydro-mechanical coupling may be salt decrepitation, observed in the laboratory at temperatures above 250°C. Two-phase flow and transport properties of the salt (porosity, permeability, tortuosity, and capillary pressure) can all change due to both mechanical deformation and chemical dissolution/precipitation (e.g., heat pipe behavior).

Two-phase flow models will consider the atmospheric pressure boundary condition applied at the drift wall, and the high brine pressure in the far-field. The initial pore pressure distribution in the salt can be simulated by starting with an undisturbed state at the time of tunnel excavation, to estimate the distribution of pore pressure around the test (Stauffer et al., 2019). Permeability and porosity are likely highest where damage has accumulated (the access drift DRZ and to a lesser extent, damage associated with drilling boreholes). Brine saturation is probably greatest in the far field, and least where mechanical damage has accumulated.

Hydrologic models will be calibrated against water inflow time series. The distribution of dry out around the heated borehole may be inferred from ERT and ultrasound travel-time tomography.

5.2.4 Chemical Models

Aqueous chemical processes in the salt include dissolution/precipitation, which can influence hydrologic and mechanical properties, especially in connected voids (fractures, bedding planes) where transport occurs in salt. Dissolution/precipitation reactions may also influence the mineral composition of precipitates such as those in the HP borehole, and the isotopic composition of sampled water in liquid or vapor form.

Modeling of mineral phases that precipitate in the borehole uses an activity model suitable for brine (e.g., Pitzer) and it is important that the associated thermodynamic database includes data for relevant aqueous species. Kuhlman et al. (2018) showed some model predictions of the evolution of mineral phases and brine composition during evaporation or boiling of WIPP-relevant brines and laboratory evaporation experiment data. Each major source of water in WIPP salt (i.e., intergranular, intragranular, and hydrous minerals) may be distinguishable by composition alone. The data from the field test will be used to help constrain these models and assess their usefulness in quantifying brine availability.

5.3 Pre-test Brine Analysis

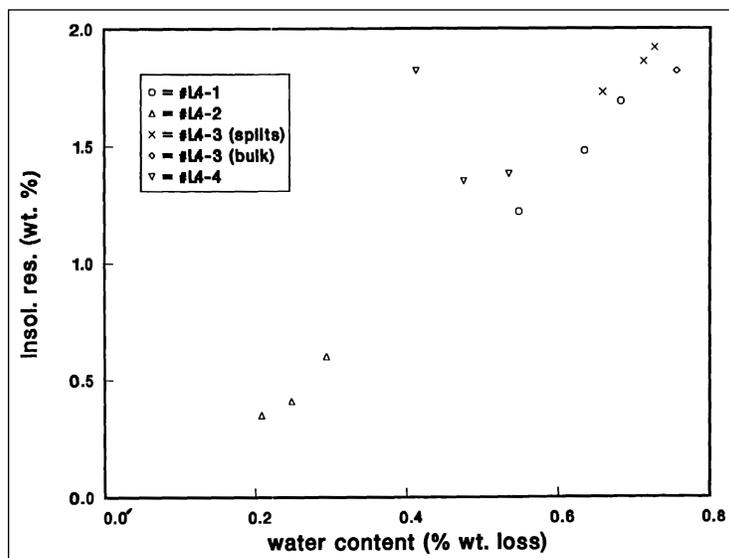
Brine that may have collected in the boreholes since they were drilled, before they are instrumented, will be collected. The boreholes will be cleaned out and video logged to document their condition before installing instrumentation. The volume of brine removed from boreholes will be documented and samples of it will be collected for compositional analysis in the laboratory. These data will provide early-time brine inflow volumes, which will be useful for calibrating hydrologic flow models, and if all boreholes produce brine, the compositional samples will provide some measure of spatial variability in the brine composition encountered in the salt. Samples will be analyzed for stable water isotopes and dissolved species components.

5.4 Core Analyses

Cores provide the best representation of rock characteristics, including m-scale to cm-scale heterogeneity encountered in the field test. They will be analyzed to describe the evaporite mineralogy and sedimentary structures. Fractures, rock damage, and core loss will be documented as well.

5.4.1 Whole-Core Analyses

The pretest 4.8 in core (HP and SL boreholes) will be imaged using X-ray CT at NETL. This analysis will quantify the percentage of non-halite minerals in the salt, based on the differences in X-ray absorption of different minerals. Bulk water content of WIPP salt from MU-0 is well-correlated with clay content (Figure 6). This information should provide a non-destructive estimate of bulk water content available in the salt. NETL may also conduct XRF mapping on the surface of the cores, and with P-wave and magnetic susceptibility profiling. These data will help identify key mineral phases encountered in the HP and SL boreholes. Geologic descriptions of any sedimentary structures, clay seams, or induced fractures will be made.



Petrographic observations using optical (e.g., reflected, refracted, and plane-polarized light) and scanning electron microscopy (SEM) of salt thin sections will be conducted on “adjacent” pre- and post-test samples (i.e., outer edge of core in pre-test sample and near the edge of borehole in post-test sample) to investigate potential impacts from heating, creep closure, and brine migration, on salt pore structure, damage-induced microstructure, and distribution of intragranular brine (i.e., fluid inclusions). Microscopic analyses may also be conducted on samples along a transect extending radially away from the heater to investigate changes in salt microstructure as a function of exposure temperature. These observations may not be used directly to quantify salt properties, but they may be used to illustrate the distribution of salt damage and deformation of fluid inclusions. Estimates of fracture density and aperture from microscopic visual inspection may help constrain the porosity of the salt. High-resolution micro-X-ray CT may also be performed on sub-core analyses for assessment of three-dimensional pore structure and mineral distribution, which may be helpful to understand flow and deformation properties.

5.5 HP – Post-Test Borehole Precipitate Analysis

After removing the packer from the HP borehole, but before over-coring it, the salt precipitate and any liquid present in the borehole will be scraped out and both solids and liquids will be sampled. A borehole camera will be used to document the condition of the borehole and the distribution of solids and liquids in it before scraping and sampling. Precipitate samples will be analyzed using X-ray diffraction (XRD) to estimate the mineral phases present and X-ray fluorescence (XRF) to determine the elemental composition of the precipitate. The mineral phase may also be analyzed by TGA to further help identify any hydrous minerals that may have formed in the borehole through their characteristic dehydration temperature. The water phase driven off during TGA may be analyzed isotopically to further constrain the fractionation models proposed to explain the stable water isotope time series collected in the HP boreholes. The isotopic makeup of hydrous salts is possibly a point of significant uncertainty in isotope fractionation models (Krause, 1983; Clynne et al. 1981).

Any liquid phases present in the borehole will be sampled and their composition will be analyzed. These solid and liquid compositional data will be used to constrain geochemical models, which predict the mineral phases that would precipitate under the observed conditions.

5.6 Gas Permeability Test Results

Pre-test and post-test gas permeability testing will primarily provide estimates of damage and secondarily provide estimates of relative gas permeability along the borehole. The tests can be interpreted using analytical solutions for simplified geometry and single-phase gas flow, or if the results deviate from simplified solutions, they may require interpretation with a more general numerical model. Single-phase flow solutions assume the wetting liquid phase is immobile, which may be valid for gas pressures below the air-entry pressure of the porous medium. Changes in relative gas permeability may be due to changes in the salt pore structure (i.e., accumulation of damage or healing) or changes in the brine content (i.e., liquid saturation). Two-phase flow solutions involve more parameters and may not uniquely predict material properties. Data from mercury injection porosimetry analysis on sub-cores may help constrain any two-phase flow solutions used to interpret gas permeability data. Either constant-pressure or pressure-decay gas permeability tests will be interpreted similar similar workflows (i.e., fitting observations to a combination of analytical and numerical predictions).

Given the expected permeabilities of the salt, the gas permeability testing is primarily to characterize the extent of damage (i.e., the DRZ surrounding the access drift—see Figure 7), since the permeability of undamaged salt will likely be below the detection limit of the apparatus and the approach being used (Beauheim & Roberts, 2002).

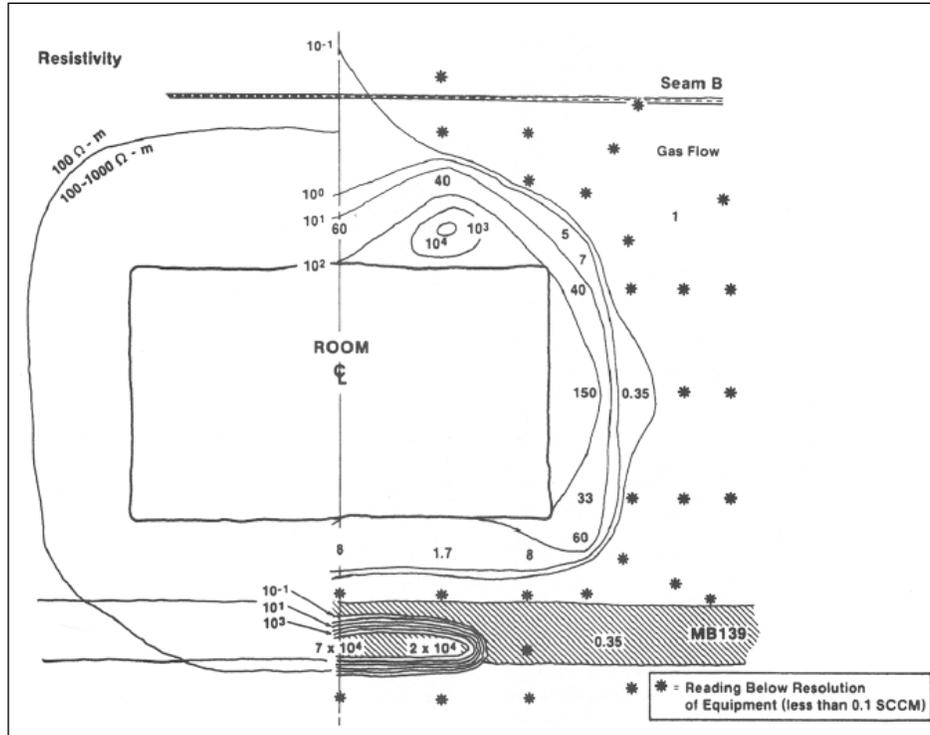


Figure 7. Results of gas flow tests and electrical geophysical surveys (Stormont 1997)

Borns & Stormont (1988) discussed the results of constant-pressure tests used to estimate the extent of the DRZ surrounding the E-1100 drift at WIPP. Blankenship & Stickney (1983) discussed procedures and results from using both falling-pressure and constant-pressure permeability tests to assess the permeability of salt in vertical boreholes surrounding a heater test at the Avery Island mine.

5.7 Data from Heater/Packer (HP) Boreholes

A large number of data are being collected in both the heated and unheated arrays at the HP borehole. This section describes how the data streams will be analyzed.

Dry nitrogen will be circulated through the interval behind the packer. The volumetric flowrate of gas through the packed interval will be controlled and known through time.

5.7.1 HP – Water Mass Flowrate Time Series

The mass flowrate of water recovered from the packed interval will be determined at a high frequency using the downstream gas flowrate and the concentration of water in the gas. The concentration of water will be measured by either the Picarro CRDS or the LI-COR 850, depending on how the three-way solenoidal switching valve is set. The Drierite desiccant canisters downstream of the gas analyzers will be weighed approximately weekly as a check on the calculation of the total mass of water leaving the borehole system from the high-frequency flowrate data.

The Picarro CRDS will be primarily connected to the outflow of the heated array, with less-frequent data obtained from the unheated array for comparison. The LI-COR 850 gas analyzer will be connected to whichever array the Picarro is not measuring. The high-frequency water concentration time series for either array will be constructed by piecing together data from the two instruments. The plumbing is set up to have separate Drierite desiccant canisters connected to the hot and ambient arrays (i.e., these data will be lower frequency, but will not require stitching together).

The water production time series will be used to quantify the mass of water entering the borehole under heated and unheated conditions. These data will be used to estimate the relative brine permeability distribution and far-field brine static formation pressure in a porous medium flow simulation (Beauheim et al. 1997).

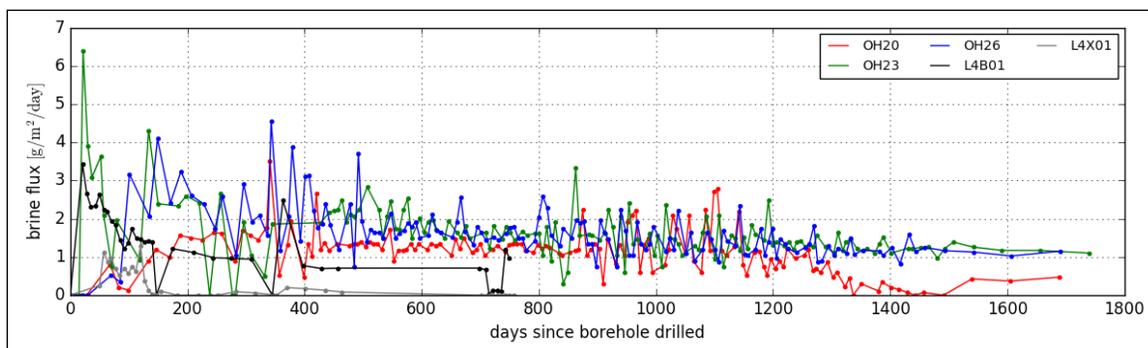


Figure 8. Brine produced from unheated horizontal boreholes at WIPP (Kuhlman et al., 2017; Data from Finley et al., 1992 and Deal et al. 1995)

Water production should be greatest just after the boreholes are drilled and will decline exponentially with time (Figure 9). The rate of water production is expected to be greater for the heated array than the unheated array (Nowak & McTigue, 1987). These data will be used to constrain numerical model predictions of both liquid and vapor water migration in the salt.

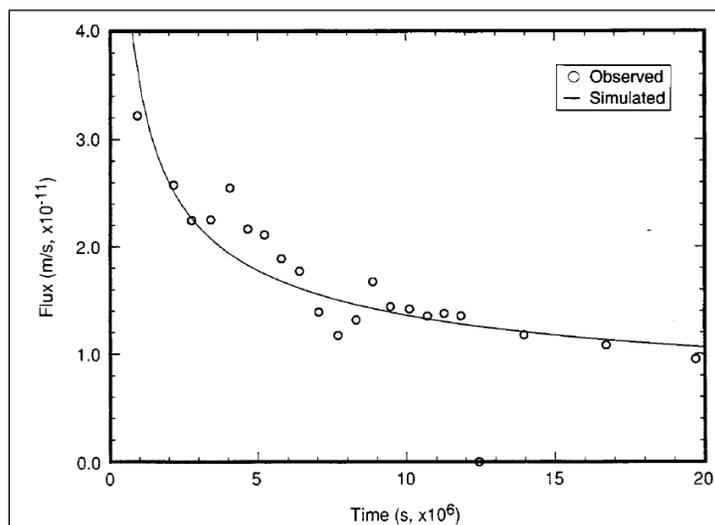


Figure 9. Comparison of McTigue (1985; 1993) model to brine inflow data from horizontal WIPP boreholes over 230 days (Beauheim et al., 1997).

The high-frequency water production time series will be a unique dataset that may show fluctuations in production due to changes in barometric pressure or mine ventilation (Figure 10). Observations of in-drift barometric pressure are needed at similar frequency to interpret results. Whenever a change in heater power occurs (up or down), brine production is expected to increase rapidly and decay exponentially (against the rapid change).

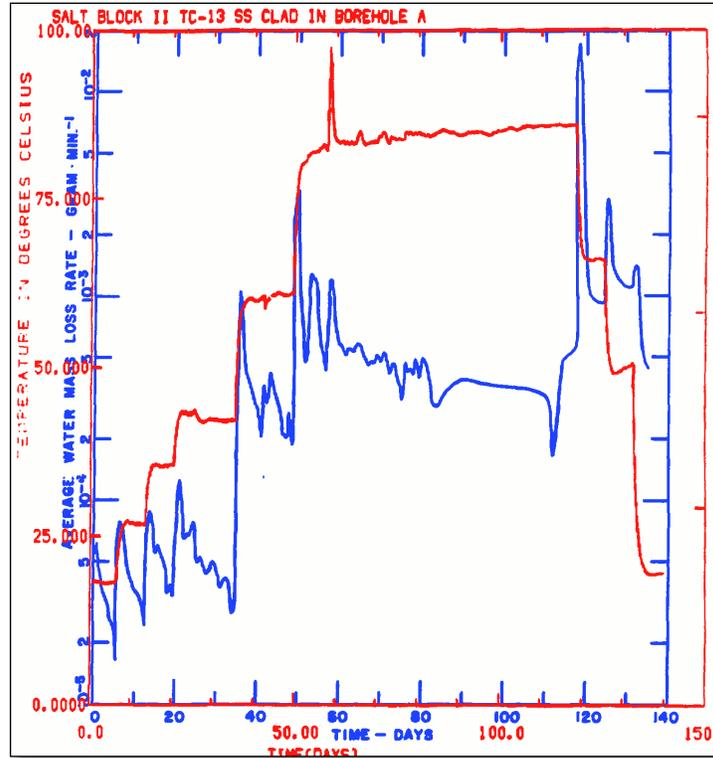


Figure 10. Water mass loss rate (blue line) and temperature (red line) observed in a large lab-scale test. Data from before 90 days were acquired by a high-frequency chilled-mirror hygrometer, while later data were obtained from daily weighing of desiccant canisters (Hohlfelder, 1979)

5.7.2 HP – Water Isotopic Composition Time Series

The Picarro CRDS will measure the relative isotopic composition of moisture in the gas stream, including both oxygen and hydrogen isotopes. The three different forms of water in the salt (intergranular, intragranular, and hydrous minerals) could have different stable-isotope signatures. The time series of water isotope fractionations may shed light on the contributions from each of the three water types before the heater is turned on, during heating, and after the heater is turned off. Isotopic differences have been observed in WIPP-relevant brine sources in the past (Figure 11). Data from WIPP fluid inclusions and anhydrite and clay layer Marker Bed 139 (MB139) show some difference in isotopic signature in historic data (Knauth & Beeunas, 1986; Lambert, 1992).

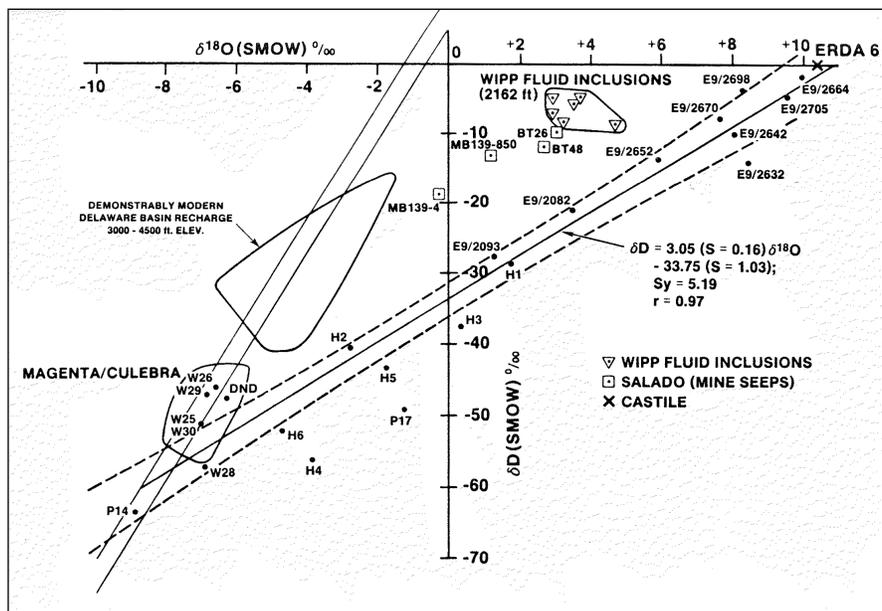


Figure 11. Stable water isotope data from WIPP site characterization studies (Lappin, 1988)

The water isotope fraction time series will be impacted by several effects: 1) evaporation as liquid brine flows into the borehole and evaporates completely or partially into the dry N_2 stream; 2) steam from dehydration of hydrous minerals, that may enter the borehole; and 3) hydrous minerals that may form in the borehole (preferentially incorporating heavier isotopes).

The relationship between δD and $\delta^{18}O$ may help detect fractionation that occurs due to evaporation in the test (e.g., Sharp, 2007; IAEA 2013). Samples will line up along evaporation lines. The difference in δD of sampled vapor could be interpretable as the fraction of tracer solution, unless brine is significantly evaporated to produce the vapor (in which case there will be a progressive shift toward heavier samples, that under-estimates the tracer fraction).

Isotopic signature time series along with brine composition from liquid samples, should help interpret how the three types of water in the salt contribute to borehole inflow under heated and unheated conditions.

5.7.3 HP – Gas Composition Time series

The gas stream from the Picarro CRDS will flow into a Stanford Research Systems Gas Analyzer (SRS QMS-200), which will record the relative concentrations of 10 different gases through time. Before the tracers are added to the D borehole, several isotopes of possible geogenic noble gases will be monitored. Starting one day before introducing the tracer gases, the relevant suite of tracer gases will be modified (He , Ar , Ne , N_2 , Kr , Xe , CO_2 , Cl , O_2 , and SF_6). These will be used to identify tracer gas introduced into the source borehole (D) and gases given off by salt (and brine) during heating, possibly including geogenic gases (e.g., isotopes of He and Ar that are trapped naturally in the salt and released due to heating or deformation).

These high-frequency data will be compared with time series of discrete gas samples collected in Mylar bags and analyzed in a laboratory with a gas chromatograph. The high frequency of data may provide a resolution of processes that cannot be observed from monthly gas samples (e.g., Figure 12)

Breakthrough of tracer gases can be used to estimate the connectivity between the D and HP boreholes through the gas-filled porosity, which should be sensitive to mechanical damage and hydrologic properties (e.g., increase gas relative permeability due to dry out). The production and transport of

geogenic gases in evaporites is still an active research topic, possibly requiring further iteration on test design. If any differential breakthrough of the added tracer gases is observed, this could provide insight into chemical processes occurring in the salt. The gas tracers all have different gas-phase diffusion coefficients and solubilities in brine, each dependent on temperature. Any differential breakthrough of gases in a single test, and any difference in breakthrough of gases between the heated and unheated arrays, may help elucidate gas-liquid or gas-solid processes in the salt.

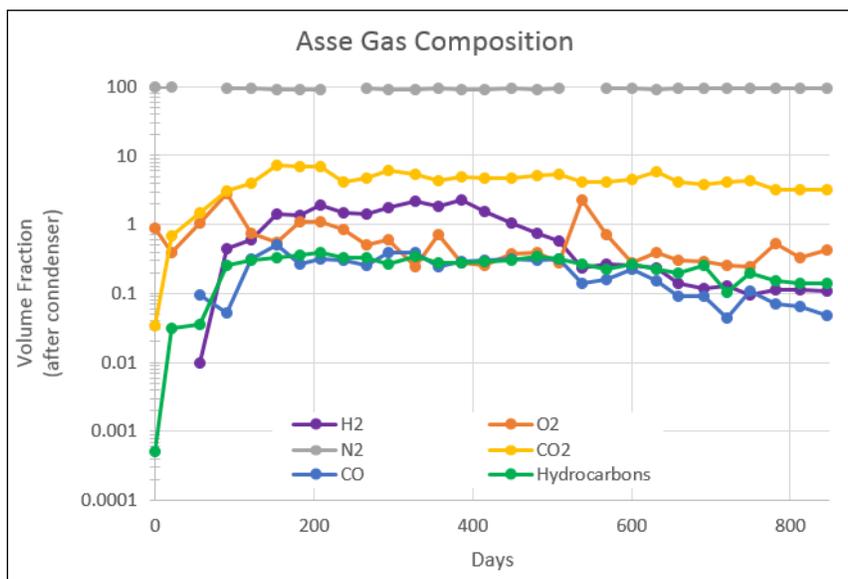


Figure 12. Non-condensable gas composition from monthly samples during Asse brine migration heater test (data from Rothfuchs et al., 1988)

5.7.4 HP – Borehole Closure Gage Time Series

The LVDT and the strain gages on the arms of the borehole closure gage will measure the closure of the HP borehole with time (i.e., change in circumference of the borehole). The strain gages will provide some redundancy to the LVDT measurement but will also allow estimation of any differential convergence (i.e., more convergence is expected to be observed vertically than horizontally). Borehole closure measurements can be used to calibrate numerical thermal-mechanical models of closure. The borehole closure data collected during the shakedown tests at WIPP has shown rapid, reversible changes associated with turning on and off the heater, which are likely caused directly by thermal expansion.

5.7.5 HP – Heater Power and Temperature Time Series

The heater controller will report voltage, current, and power applied to the heater, which is critical to characterizing the applied thermal boundary condition. The controller will also report the temperature at thermocouples inside the borehole used to control and provide an over-limit safety for the heater. This will be used in thermal-hydrologic-mechanical models, driving the thermal response of the entire system. Only the HP borehole in the heated array will be collecting this time series.

5.7.6 HP – Total Gas Pressure and Molar Flowrate Time series

The volumetric total flowrate of gas entering and leaving the borehole can be used to constrain the leakage of the borehole (i.e., the relative gas permeability) through time. Analysis of changes in the net leakage of the packer-borehole system through time may be used to infer temporally how any changes in permeability between pre-test and post-test results may have occurred.

5.8 Data from Acoustic Emission (AE) Boreholes

The piezoelectric transducers in the AE boreholes will be used to passively monitor for acoustic emissions and to actively conduct ultrasound travel-time tomography. Thermocouples associated with the transducers will be used to provide additional locations for monitoring the thermal response of the test to heating. A total of 16 channels which will be used between the two Mistras logging systems for the two arrays (heated and unheated). For the majority of the time the logger, as a 16-channel system, and sensors will mostly be in the AE boreholes of the heated array. At other times one or both of the Mistras systems, whether an eight- or 16-channel unit, will record data at the unheated array for comparison.

5.8.1 AE – Acoustic Emissions Time Series

The AE systems monitoring each array will be used to listen for acoustic emissions, from damage in the salt due to heating, cooling, and brine migration. The Mistras logger will automatically identify acoustic emissions, based on hits occurring on multiple channels defined by threshold crossings and similar waveform characteristics. The frequency of acoustic emissions will likely be much higher during increases and decreases in heater power (Figure 13). The AE events are associated with shear or extensional damage. This damage is associated with an increase in porosity and permeability in the salt.

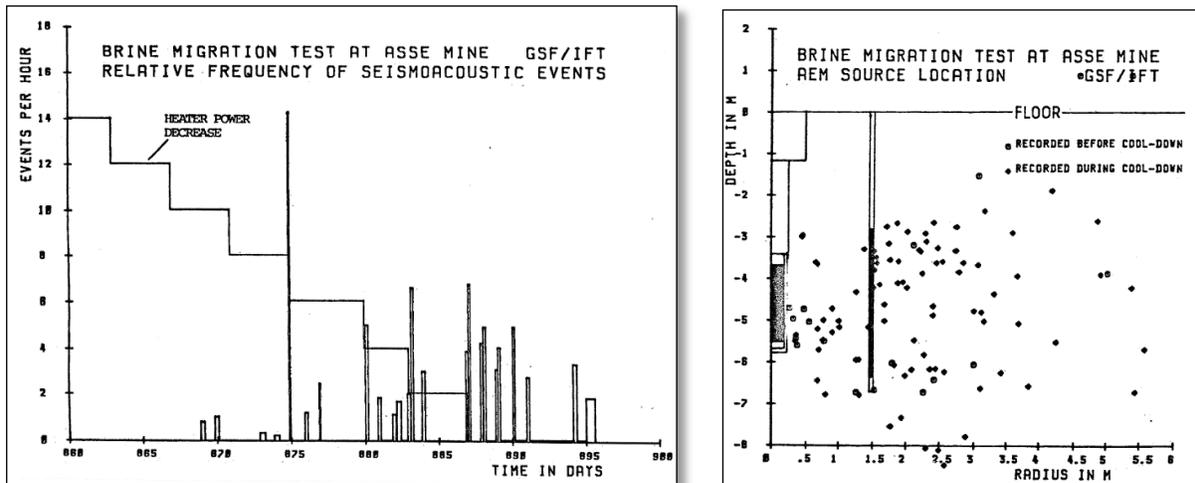


Figure 13. Acoustic emissions during Asse brine migration heater test (Rothfuchs et al., 1988)

The arrival times taken from full-waveform data digitized from the sensors can be used to locate the source of an acoustic emission (given enough of the sensors record an event to triangulate it in three-dimensional space). Estimating the source location of the acoustic emission events, provides some information on the locations of the changes in porosity and permeability.

The AE dataset can be used with the water inflow time series to validate hydrologic-mechanical flow models. The AE dataset will show where damage has occurred (Holcomb et al., 2001), which is related to where changes in permeability are occurring in the salt. Changes in porosity and permeability can impact the amount of brine flowing into the borehole and will be related to the changes in permeability between pre- and post-test gas permeability testing.

5.8.2 AE – Ultrasonic Wave Travel-Time Test Results

The eight AE sensors not used as observation locations in each array (24 piezoelectric transducers are installed in the array being listened to) can be used as sources for active ultrasound travel-time tomography. A square-wave “ping” is applied to each of the source sensors (one at a time), while listening to the 16 passive sensors attached to the Mistras system. The ultrasonic wave travel time through

the salt between each source and receiver pair is observed. This active source is driven manually, but implemented periodically (e.g., bi-weekly) to monitor any relative changes in ultrasound travel time in space and time.

The ultrasonic wave travel time through the salt is a function of compressional velocity, which is affected by temperature, porosity, heterogeneity, and brine content. The survey data will be processed by fitting a forward wave travel-time model (i.e., a straight-ray model) and incorporating changes in the resulting velocity model in terms of some or all of these effects. Changes in the velocity model can be used to refine the acoustic emissions location analysis. The ultrasonic wave travel-time tomography may be able to image changes in ultrasonic slowness around the heater. Further interpreting these changes to be due to changes in temperature or saturation may require careful laboratory testing on representative samples of salt.

Moving the sensors between the heated and unheated arrays may introduce errors or complications in the interpretation of the AE data or the ultrasonic travel-time tomography, associated with getting the sensors to the same locations.

5.9 T – Temperature Time Series

A large number of Type-K thermocouples are located in the two T boreholes, and more are co-located with other observations in other boreholes (i.e., AE, F, and E). In the heated array, the distribution of temperature observations will be used to characterize thermal conduction, and changes in the conduction with location (e.g., due to local temperature) and time during the test. Temperature data will also be used to infer the presence of convective heat transport, and to understand the thermal influence of the drift wall.

The temperature distribution will be simulated as part of thermal-mechanical and thermal-hydrologic simulations, since conduction is the primary means of heat transfer. Inside un-grouted boreholes there may be free convection. Free convection may also occur in gas-filled porosity where the temperature is greater than the brine boiling temperature (and it is likely that dewatering will occur). There will be radiation between the quartz lamp heater and the borehole wall (and re-radiation between surfaces on the wall with different temperatures). Where important, convection and radiation will be included in the interpretation of thermal processes.

Getting the temperature distribution correct is important because hydrologic and mechanical processes are driven by changes in temperatures of the salt. The mechanical and chemical properties of salt are temperature-sensitive, and brine will migrate away from regions of higher temperature because of fluid pressure associated with thermal expansion.

5.10 E – Apparent Resistivity Test Results

Electrical resistivity tomography surveys between the three ERT boreholes will be used to estimate the 3D distribution of apparent electrical resistivity in the volume enclosed by the arrays. Apparent resistivity of the salt is primarily a function of brine content and temperature, and may also be influenced by stratigraphy, differences in porosity, and man-made metal objects. The damaged region associated with an excavation tends to have higher resistivity than intact salt (Figure 7).

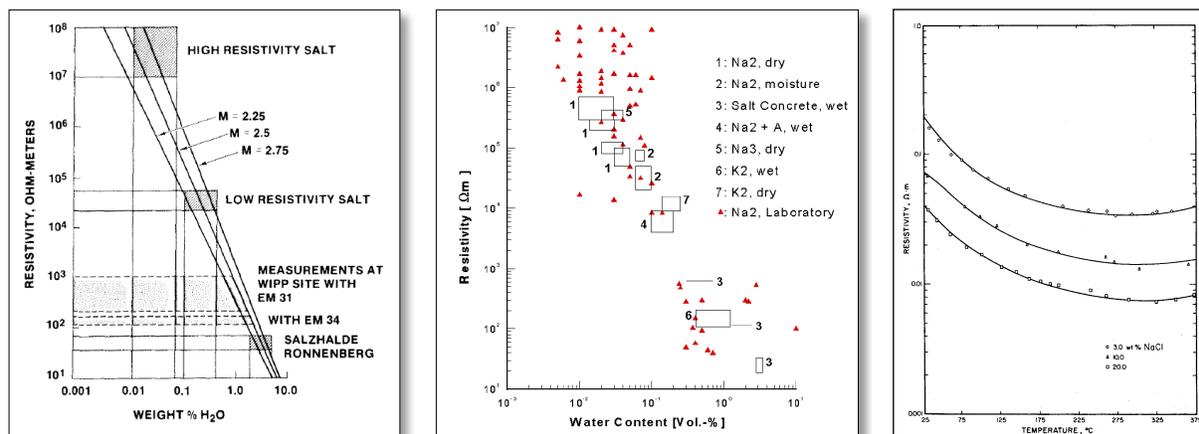


Figure 14. Left: resistivity of salt as a function of water content at WIPP (Skokan et al., 1989), (middle) and at Asse (Jockwer & Wiczorek, 2008), and (right) resistivity as a function of temperature and salinity (Ucok et al., 1980)

The interpreted ERT apparent resistivity tomograms will show changes in resistivity distribution with time. Changes in apparent resistivity can be attributed to changes in temperature and water content (Figure 14), since salt heterogeneity and added metal in the test should not change with time. ERT may be able to image an expanding dry out region surrounding the heat source, especially if the salt temperature around the heater exceeds the brine boiling point (promoting dry out). The ERT tomograms will be jointly interpreted with ultrasonic travel-time tomography and acoustic emission, to detect anomalous regions where dilation, boiling, and other processes may occur.

The ERT controller and electrodes that will be used have already been tested in boreholes at WIPP as part of the shakedown testing. The inverted results of the baseline resistivity structure and the signal from brine migration are shown in Figure 15.

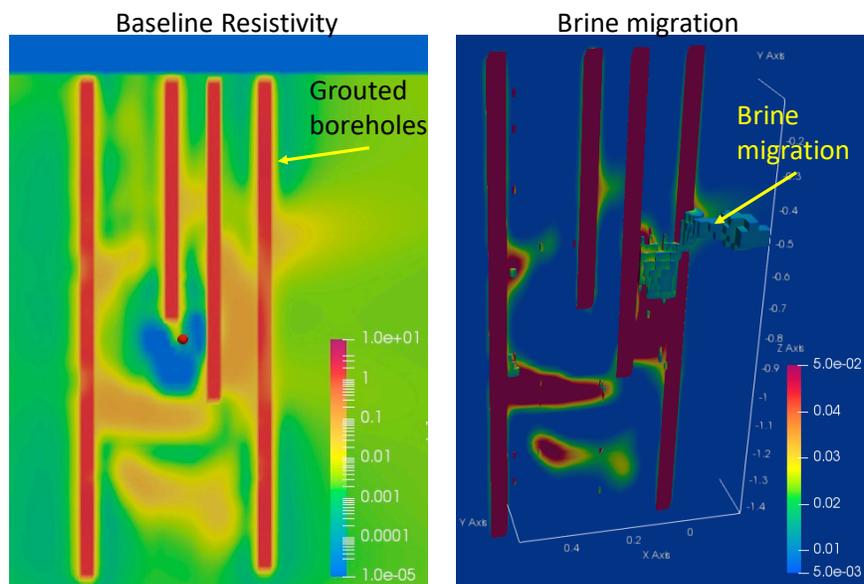


Figure 15. Baseline electrical resistivity structure [S/m] during shakedown test (left) and visualization of brine migration pathways during a brine injection test (right)

5.11 F – Fiber Optic Distributed Sensing Time Series

5.11.1 F – Distributed Strain Time Series

The longer fiber boreholes in each array (F2) will collect longitudinal strain data along the length of the fiber optic cable. The strain profile will extend into the far-field (30-ft [9.1 m] deep into the pillar) and will be used to show the deformation along the length of the F2 borehole with time. This strain measurement is precise and will be acquired at high frequency. Comparing the data between the heated and unheated arrays will quantify the timing and extent of deformation associated with heating the HP borehole. These data will be useful for validating results of thermal-mechanical simulations.

5.11.2 F – Distributed Temperature Time Series

The distributed temperature data will be a high-resolution distribution of temperature along the fiber and will complement the thermocouple data, already discussed above. Measuring the temperature distribution in the F2 borehole, will include observations more than 20 ft [6.1 m] from the heater, far away from the effects of the drift. These data will be useful in constraining and validating boundary conditions or domain size of thermal-mechanical and thermal-hydrologic numerical models.

5.12 D & SM – Source and Liquid Sample Test Results

Gas and liquid sources will be introduced into the source borehole (D). Gas-phase tracers will be monitored at high frequency in the gas stream from the HP borehole using the SRS Gas Analyzer. The stable-isotopic signature of the liquid-phase tracer will also be monitored at high frequency in the gas stream from the HP borehole using the Picarro CRDS. The liquid-phase dissolved tracers (i.e., perrhenate and Na-naphthionate) will be monitored by weekly sampling in the liquid-phase sampling borehole (SM). Liquid samples will be analyzed for changes in concentration of introduced tracers and the primary species present in the natural brine. These data will help constrain the liquid phase of flow and transport models.

5.13 SL – Seal Borehole Time Series and Test Results

The seal portion of the experiment will include strain and temperature data collection and may run for an extended period of time before the cement plugs are over-cored to observe salt/cement interactions.

5.13.1 SL – Strain and Temperature Time series

The lab-constructed seals will be instrumented with strain gages to observe strain in the salt once the borehole has closed in and made contact on the laboratory-fabricated cement plugs. The strain gages in the cement plugs will be configured to observe three components of strain and temperature (via thermistors). The strain gages in the seal will provide strain data, which is additional information to constrain a geomechanical model of borehole deformation, away from the heated borehole (assuming the properties of the cement plugs are well-known). The borehole plug at the drift side of the SL borehole will monitor RH and air temperature in the borehole between the plug and the drift.

5.13.2 SL – Salt, Brine, and Cementous Material Interactions Analysis

After the rest of the test is complete (months to years later), the SL borehole plugs will be over-cored to examine the interaction between the cements (salt concrete and sored cement), the salt surrounding the borehole, and any brine which has flowed into the borehole during the test. Any liquid brine in the borehole will be sampled for compositional analysis before over-coring. If required for stability reasons, the open part of the SL borehole may be plugged with epoxy before over-coring (e.g., Mäder et al., 2016). The over-cored samples will be analyzed via CT scanning at NETL, just as the pre-test cores were analyzed. Sub-cores across the salt-cement interfaces will be collected for petrographic (optical and SEM analysis of thin sections), mineralogical, and micro-CT analyses. The samples will be characterized for

evidence of alteration of the salt or cementitious materials. Such investigations will include examining samples as a function of distance from the salt-cement interface.

These analyses will provide information for validation of chemical models of mineral alteration, in both the salt and cements at and in the vicinity of the salt/cement interface. As a field-scale version of experiments done as part of the Full Scale Demonstration of Plugs and Seals (DOPAS) sealing test conducted by Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) (Figure 16), this test will complement the lab-scale tests that investigated the coupling between mineralogic alteration and permeability at the salt/cement interface.

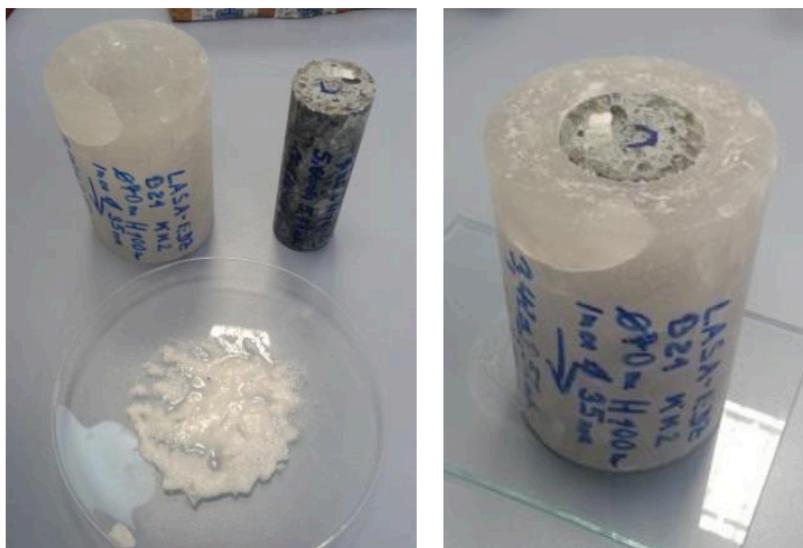


Figure 16. Laboratory-scale salt/seal interaction test at GRS (Czaikowski et al., 2016)

6. Implementation and Next Steps

During the field implementation of the BATS test at WIPP, there may be deviations from the plan laid out here. Revision of this report in September 2019 will update the information given here, to present an “as-built” description of the test, with preliminary early data.

Lessons learned from the implementation of this field test will be considered in the design and implementation of any future field tests at WIPP.

As of the time of writing version 1 of this report (April 2019), the WIPP shakedown tests (Boukhalifa et al., 2018) have been going on for several months, and have tested key aspects of the design, including: comparison between Drierite desiccant and dry N₂ gas circulation for estimation of water production, heater design and power, grouting of thermocouples, conducting ERT surveys in salt, brine sampling from horizontal boreholes, connecting the SRS and LI-COR gas analyzers to the N₂ gas stream, and packer design. In the SDI area, new boreholes have been drilled and cored for the heater test outlined here, but the equipment has not yet been installed in them. The tests outlined here will be implemented in these boreholes in the upcoming weeks and will be summarized in the upcoming revision of this report in September.

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APPENDIX E NTRD DOCUMENT COVER SHEET¹

Name/Title of Deliverable/Milestone/Revision No. Salt Heater Test (FY19)

Work Package Title and Number Salt Disposal R&D - SNL

Work Package WBS Number SF-18SN01030303

Responsible Work Package Manager Kristopher L. Kuhlman. 
(Name/Signature)

Date Submitted: 04/30/2019

Quality Rigor Level for Deliverable/Milestone ²	<input type="checkbox"/> QRL-1	<input type="checkbox"/> QRL-2	<input checked="" type="checkbox"/> QRL-3	<input type="checkbox"/> QRL-4 Lab QA Program ³
	<input type="checkbox"/> Nuclear Data			

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 Other

This Deliverable was subjected to:

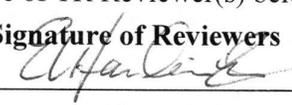
Technical Review

Technical Review (TR)

Review Documentation Provided

- Signed TR Report or,
- Signed TR Concurrence Sheet or,
- Signature of TR Reviewer(s) below

Name and Signature of Reviewers

Ernie Hardin 

Peer Review

Peer Review (PR)

Review Documentation Provided

- Signed PR Report or,
- Signed PR Concurrence Sheet or,
- Signature of PR Reviewer(s) below

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 NTRD Document Cover Sheet.

- 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.

NOTE 2: If QRL 1, 2, or 3 is not assigned, then the QRL 4 box must be checked, and the work is understood to be performed using laboratory QA requirements. This includes any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.

NOTE 3: If the lab has an NQA-1 program and the work to be conducted requires an NQA-1 program, then the QRL-1 box must be checked in the work Package and on the Appendix E cover sheet and the work must be performed in accordance with the Lab's NQA-1 program. The QRL-4 box should not be checked.