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Spent Fuel and Waste Disposition (SFWD) Program

Test/Activity Plan

Summary of the Brine Availability Test in Salt (BATS), Including Extended Plan for Experiments at the Waste Isolation Pilot Plant (WIPP)

Spent Fuel and Waste Science & Technology (SFWST) Milestone: M3SF-24SN010303053

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Test Plan Introduction and Motivation

This document lays out a set of near-future investigations in salt, the third phase of BATS (BATS 3). This phase is planned to answer the few remaining issues from the first two phases of BATS (BATS 1 and BATS 2), and to prepare for a subsequent large-scale demonstration phase. The BATS experiments are the first part of a larger plan to conduct field experiments to answer specific technical questions, improve the technical basis for disposal of heat-generating radioactive waste in salt (Stauffer et al., 2015; SNL et al., 2020), and demonstrate readiness for disposal of radioactive waste in salt, including large, hot waste packages.

The tests proposed as part of BATS 3 can be divided into experiments and method development, which can be grouped into four primary technical themes:

1. Damage (Excavation Damaged Zone - EDZ) evolution:

   Because salt is impermeable in the far-field, the characterization of the evolving damage in the salt is key to predicting the amount of brine which may be produced in an excavation and is the initial condition for long-term performance assessment.

2. Brine characteristics:

   Salt brine samples vary in chemical and isotopic composition, depending on their source (i.e., fluid inclusions or clays) and transport. Refining this understanding allows us to better understand where brine is coming from, and best design future systems to minimize any adverse brine inflow effects, to the extent possible.

3. Heat effects:

   Heated salt behaves quite differently than unheated salt. For heat-generating waste, it is critical to understand and be able to predict the impacts that heat has on the migration of gas and brine, and the ultimate healing of the damage zone back to undisturbed conditions.

4. Engineered barrier systems (EBS) interactions with salt and brine:

   Since the salt is impermeable, sealing of man-made excavations (i.e., drift and shaft seals) is critical in any future salt repository. The development and testing of man-made materials to seal these openings, while being compatible with the native salt and brine requires field-scale testing.

This document presents a series of experiments and methods to better understand and characterize these processes, while preparing for the next phase of testing, which will include an increase in scale (i.e., physical size and time duration of testing), to illustrate readiness for implementation of a repository for heat-generating waste in salt.

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ABBREVIATIONS AND ACRONYMS

CBFO	Carlsbad Field Office (DOE-EM Field Office managing WIPP)
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
EBS	engineered barrier system
EDZ	excavation damaged zone
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
M&O	management and operations (SIMCO at WIPP)
R&D	research and development
SIMCO	Salado Isolation Mining Company (WIPP M&O contractor)
SFWST	Spent Fuel and Waste Science and Technology (DOE-NE campaign)
SNL	Sandia National Laboratories
TCO	WIPP Test Coordination Office (managed by CBFO)
THMC	thermal-hydrological-mechanical-chemical
TRL	technical readiness level
URL	underground research laboratory
WIPP	Waste Isolation Pilot Plant (DOE-EM facility managed by CBFO)

1.0 BACKGROUND

This document is a high-level test plan for small-scale experimental activities at the Waste Isolation Pilot Plant (WIPP) funded by DOE Office of Nuclear Energy (DOE-NE). This document is an update of the previous Brine Availability Test in Salt (BATS) plan document from 2021, which had been completed before implementation of the second phase of BATS (Kuhlman et al., 2021a).

The DOE-NE Spent Fuel and Waste Science & Technology (SFWST) Research & Development (R&D) campaign seeks to provide a sound technical basis for multiple viable radioactive waste disposal options. The desired outcomes of the R&D program are increased confidence in the robustness and readiness of generic disposal concepts and fit-for-purpose science and engineering tools needed to support disposal concept implementation. Sandia, Los Alamos, and Lawrence Berkeley national labs are conducting research on salt as a candidate disposal medium for spent nuclear fuel and other heat-generating DOE-managed wastes. This research includes the BATS field experiments conducted underground at the WIPP, a DOE Office of Environmental Management (DOE-EM) Carlsbad Field Office (CBFO) facility for disposal of transuranic defense waste. DOE-NE works through the WIPP Test Coordination Office (TCO) to leverage the existing WIPP underground experimental infrastructure to advance science on generic disposal concepts. The WIPP TCO works for the CBFO Chief Scientist during the planning and implementation of the BATS field test.

The BATS experiments are a set of small-scale borehole experiments at WIPP designed to explore the importance of brine availability in the presence of host rock damage and elevated temperature during the possible future disposal of heat-generating waste in bedded salt, under the generic (i.e., not site-specific) SFWST R&D campaign. This research is relevant to the temperatures expected for DOE-NE managed wastes (including spent fuel), as opposed to previous experimental work at WIPP relevant to non-heat generating transuranic waste or defense high-level waste (Matalucci, 1987a). Brine availability includes characterizing:

- the amount and types of brine present in the salt; and
- the evolution of pathways that exist for this brine to reach excavations (i.e., boreholes and drifts).

The primary pathways for flow of liquid and gas through the salt are fractures in the Excavation Damaged Zone (EDZ), which is a halo of damaged salt with altered properties surrounding rooms or boreholes in the underground.

Within this document we present the plan for future investigations in salt. The third phase of BATS (BATS 3) is planned to address the few remaining issues from the first two phases of BATS (BATS 1 and BATS 2), and to prepare for a subsequent large-scale demonstration phase. The BATS experiments are the first part of a larger plan to conduct field experiments to answer specific technical questions, improve the technical basis for disposal of heat-generating radioactive waste in salt (Stauffer et al., 2015; SNL et al., 2020), and demonstrate readiness for disposal of radioactive waste in salt, including large, hot waste packages.

2.0 PURPOSE AND SCOPE

This test plan describes the possible activities to enable implementation by an appropriate technical team. The general objective is to characterize the distribution and evolution of brine and damage around excavations in salt, and how the brine and damage change in response to elevated and changing temperature, the thermal-hydrological-mechanical-chemical (THMC) EDZ evolution.

The high-level technical objectives and motivation of the test plan are:

- Reducing uncertainty in performance assessment models of salt repository systems for heat-generating waste through better understanding of physical processes (THMC).
- Measure the thermal-mechanical (TM) response of the salt from heating (i.e., temperature distribution and creep resulting in drift and borehole closure), since heat is the primary difference between the investigations carried out for the WIPP mission and those for DOE-NE relevant wastes.
- Quantify brine inflow from the damaged salt to boreholes (i.e., thermal-hydrological – TH), measuring gas and water composition to better understand source of water (e.g., fluid inclusions, water from clay, hydrous minerals), since understanding the sources of brine may allow the design of a future repository to avoid or minimize effects of brine.
- Use modern geophysical methods (e.g., electrical resistivity tomography (ERT), fiber optic distributed temperature and strain sensing, acoustic emissions) to obtain more accurate data for characterizing the evolution of the salt and brine during heating, cooling, and application of gas pressure in packer-isolated intervals (THM). Many new or improved geophysical methods exist since earlier testing at WIPP (1980s to early 1990s).
- Collect pre- and post-test samples of intact salt (i.e., cores, precipitated salt), brine, and precipitated salts for lab analyses (i.e., thermal conductivity, electrical resistivity, chemical composition, and X-ray computed tomography), since it is impractical to bring all these advanced laboratory characterization methods to the field (i.e., we still need these methods to reduce uncertainties associated with the effects of heating on salt and brine).
- Observe the interactions between seal materials (e.g., salt concrete or Sorel cement), host rock (i.e., halite, clay, anhydrite, and polyhalite), and brine under both heated and unheated conditions, since the sealing of man-made excavations in salt is critical to a successful repository design and advances in sealing materials since the 1980s should be included. These sealing experiments are stepping stones to field-scale demonstrations for repository seals, possibly relevant to both DOE-EM and DOE-NE missions.

The main scientific question that motivated the BATS 1 test centered on *brine availability*. Understanding brine availability requires investigation into two related things: first, quantifying the types and amounts of brine distributed through the salt; and second, the time and space distribution of pathways in the excavation damaged zone that allow movement of this water towards boreholes and drifts. Water in bedded salt (~0.5 to 1.8 % by volume) is found in fluid inclusions, disseminated clay, and hydrous minerals (e.g., polyhalite). Each of these water types and their potential flow paths respond differently to changes in stress or temperature. Salt far from the excavations is impermeable and has very low porosity (e.g., Roberts et al., 1999; Beauheim & Roberts, 2002). The salt near excavations is damaged (i.e., the Excavation

Damaged Zone or EDZ), which includes fractures that may allow flow of gaseous and liquid water depending on their connectivity. The salt EDZ accumulates further damage and healing from heating and cooling due to thermal expansion/contraction and creep, resulting in temperature-, stress-, and moisture-dependent properties to characterize.

While working to understand these scientific questions and technical objectives of BATS, the overarching goal of the SFWST campaign in salt is to gather data to refine our understanding and improve readiness of salt as a disposal medium for heat-generating waste. We seek to better understand the nature and evolution of the EDZ and the distribution of brine in the EDZ. The state of the EDZ (i.e., its condition and properties) is an important initial condition to long-term repository performance assessment.

2.1 Previous and Current BATS Phases

2.1.1 BATS Shakedown Test

The first preliminary phase of BATS (phase 1s, for "shakedown") located in E-140 drift (Boukhalfa et al., 2019) was focused on confirming the viability of several key BATS experimental methods and equipment in the WIPP underground. The shakedown tests used existing horizontal boreholes drilled as part of a previous (2012 to 2013) coring campaign. These shakedown tests provided useful design information regarding the heater design, gas circulation, and sampling methods. The shakedown tests also provided useful data (temperature and water production) for benchmarking numerical and conceptual models (Guiltinan et al., 2020), but were implemented mostly to prepare for the next phase of testing.

2.1.2 BATS 1 Test

BATS Phase 1 (BATS 1) was conducted in two arrays with 14 horizontal boreholes each, drilled in the N-940 drift (Kuhlman et al., 2020; Figure 1). One array was instrumented and heated, and a second similarly instrumented control array was monitored, but unheated. The boreholes were drilled in Map Units 1 to 4 (Figure 2) from February to April 2019. After assembling the required infrastructure and instrumenting the boreholes, the first phase of heating in the BATS 1 heated array occurred during January to March 2020 (also called BATS 1a).

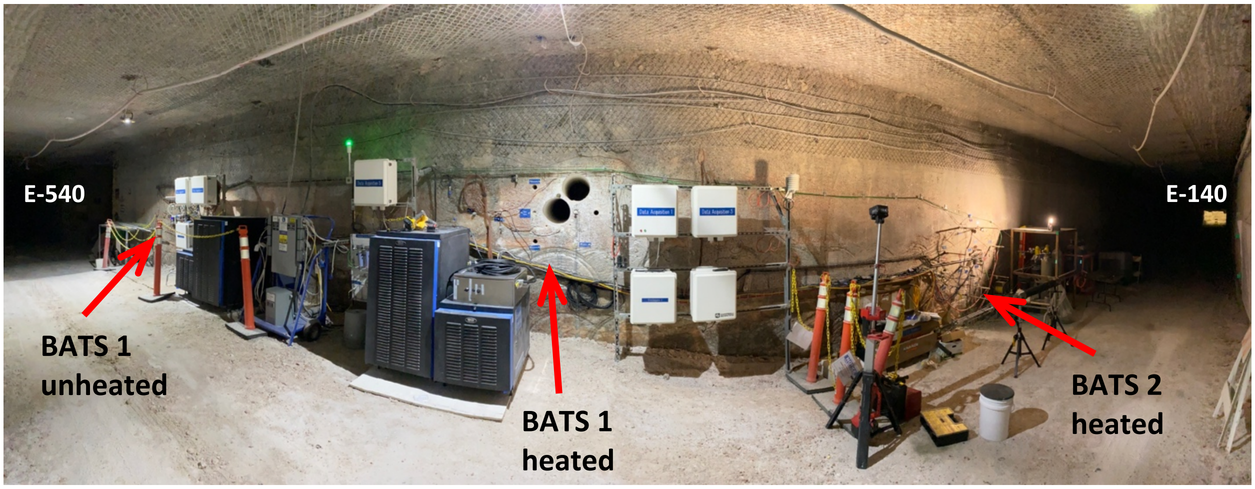


Figure 1. Panoramic photo of BATS in N-940 drift (looking south) showing BATS 1 unheated (left) and BATS 1 heated (middle, with over-core boreholes visible), and BATS 2 heated (right).

BATS 1 circulated dry N_2 gas continuously through the heated region (750 W heater along 69 cm of borehole 2.75 m deep) behind an inflatable packer, and measured composition of the gas stream coming off the salt at a 5-minute sampling rate with in-drift analysis. In the gas stream, water isotopes were monitored with a cavity ringdown spectrometer, and the gas composition was monitored with a quadrupole mass spectrometer. The temperature distribution was monitored at ~200 locations through time with thermocouples. Electrical resistivity tomography was used to infer the distribution and movement of brine (i.e., cool, dry salt is more resistive than hot, wet salt) due to heating and movement of gas (Wang et al., 2023). Acoustic emissions were monitored during heating and cooling, with ~75% of all emissions observed coming from thermal contraction associated with the cool-down phase.

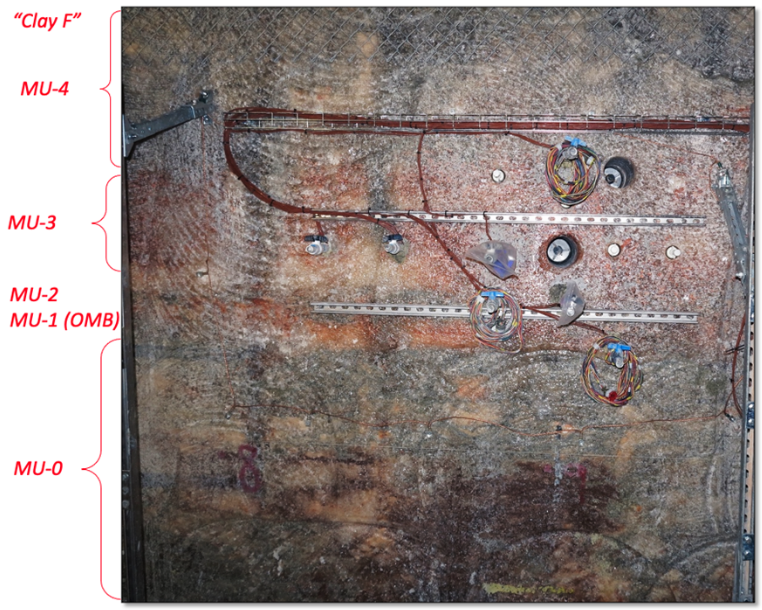


Figure 2. BATS 1 array with WIPP Map Units (MU) indicated (Kuhlman et al. 2022). OMB is the orange marker band.

The data acquired during the first heater test of BATS 1 were used in Task E of the international modeling validation exercise DEvelopment of COupled models and their VALidation against EXperiments (DECOVALEX; Kuhlman, 2020; Kuhlman et al., 2024). This modeling exercise has shed light on several aspects of brine availability and has also revealed several aspects of test design that were improved in the subsequent phase, BATS 2.

Several rounds of heating while injecting gas and liquid tracers into the packer-isolated intervals in the tracer source (D) borehole. Breakthrough was monitored via continuous monitoring of the central heater and packer (HP) borehole and samples collected from the sampling (SM) boreholes – see Figure 3). The most direct way to quantify important transport properties of the EDZ (advective porosity and permeability) is to flow tagged gases or liquids through the salt, from one borehole to another. Brine production into the central heater and packer (HP) borehole appears influenced by pressurization of gas in the D borehole, as part of permeability and tracer tests.

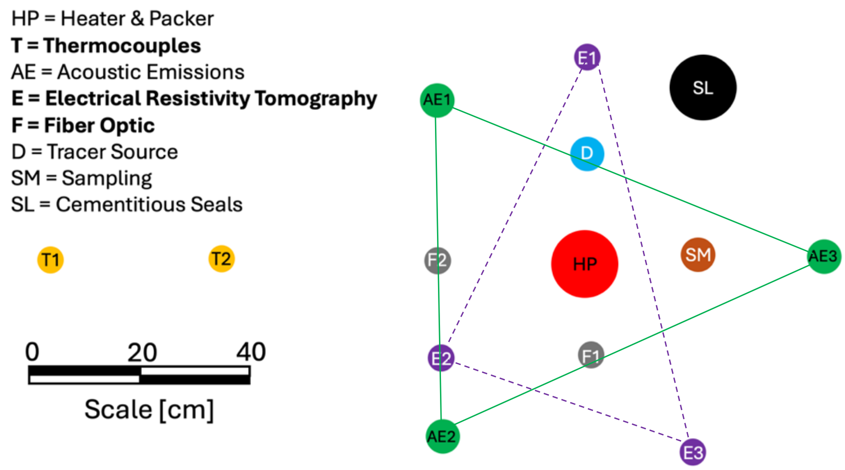


Figure 3. Drift-view layout of boreholes in BATS 1 illustrating triangles created around HP borehole by AE (solid) and ERT (dashed) boreholes. Bolded names indicate grouted boreholes.

2.1.3 Destructive Post-Test BATS 1 Sampling

The BATS 1 heated array HP heater/packer assembly, the D packer, the seal (SL) mechanical packer, and the SM mechanical packer were removed. The boreholes were scraped and sampled for precipitated salts. The HP and SL boreholes were stabilized with grout. As part of the mobilization of drilling equipment and personnel to drill a new heated array for BATS 2, the HP and SL boreholes were over-cored (Figure 3). These cores will be compared to pre-test cores collected in 2019 from HP and SL boreholes, to provide laboratory samples.

Figure 4. BATS-1 over-coring; left: WIPP TCO processing over-core, right: over-core on pallets.

These over-cores have been brought to Sandia National Laboratories, Albuquerque for quantification of:

- the effects of heating on the salt (samples around the HP borehole);
- the nature (size, shape) and distribution of fluid inclusions (i.e., evidence for their movement under a temperature and stress gradient around the HP borehole);
- the distribution of liquid tracers added to the salt in BATS 1c (i.e., salt between the D and HP boreholes); and
- interactions between native salt, brine, and cementitious seal materials (the SL borehole).

As of 2024, these analyses are still underway at Sandia. Storing, handling, and subsampling the large cores has required updates to laboratory procedures to accommodate large, heavy cores (i.e., cores weigh ~1.5 kg/cm [100 lb/ft], and approximately 5.8 m [19 ft] were collected).

2.1.4 BATS 2 New Heated Array

To better characterize the brine released from the salt immediately after drilling, the heated BATS 2 array was coordinated to be drilled, instrumented, and tested in a shorter time frame (~5 months) than was possible in BATS 1 (>11 months). Brine inflow rate in a newly drilled borehole decays rapidly from an initial peak, requiring a coordinated effort to observe early time behavior. The BATS 2 heated array was drilled at a lower elevation and immediately west down the N940 drift, near where the gas cylinder rack was in BATS 1 (see Figure 1).

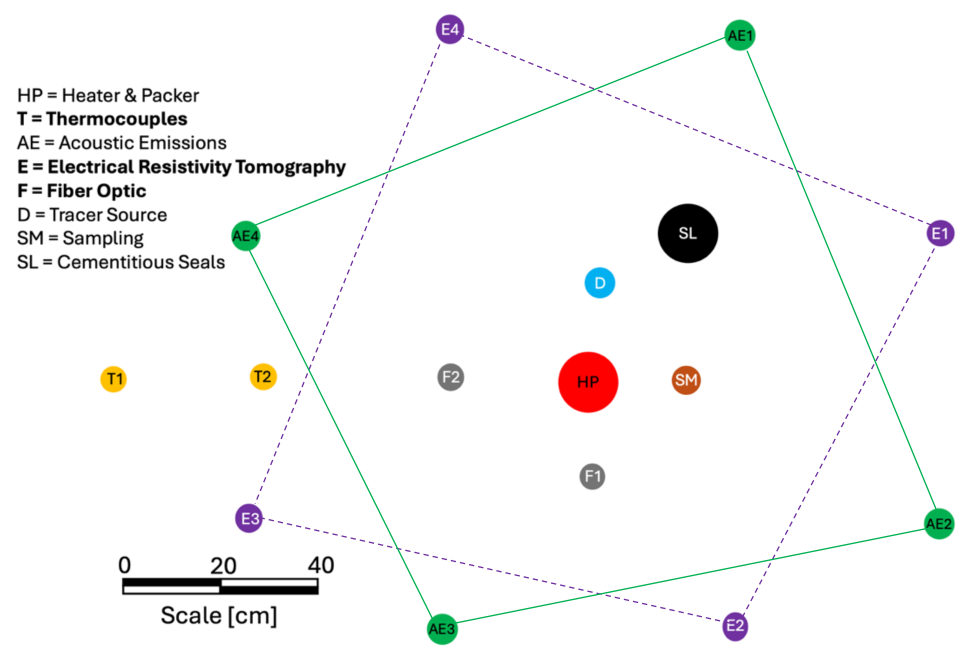


Figure 5. Drift-view layout of boreholes in BATS 2 illustrating shapes created around HP borehole by AE (solid) and ERT (dashed) boreholes. Bolded names indicate grouted boreholes.

The BATS 2 heated array was constructed like BATS 1, with the following improvements:

- Liquids were sampled from open boreholes regularly, starting immediately after drilling (including a new sponge-based sampling system, that allowed sampling smaller inflows than in BATS 1).
- The BATS 2 heated array was completed at a lower stratigraphic unit, argillaceous MU-0. BATS-1 was completed in the clean halite of MU-3 (Figure 2).
- The acoustic emissions (AE) and electrical resistivity tomography (ERT) boreholes were drilled radially further from the central HP borehole, splitting the sensors between four instead of three boreholes (compare Figure 3 to Figure 5).
- Most BATS 2 boreholes were 30 to 61 cm [1 to 2 ft] longer than they were in BATS 1, to locate more of the instrumentation deeper into the salt, closer to the heater, and further from the access drift EDZ.
- Boreholes with grouted instruments were drilled at 5.3 cm [2.1-in] diameter, rather than 4.4 cm [1.75-in] diameter, to simplify installation.
- Grout was emplaced using a new, larger grout pump.
- Non-expansive grout was used for thermocouples, ERT, and fiber optics (bold borehole names in Figure 5). Less problematic brine leakage was observed through instrumentation wires in BATS 2, compared to BATS 1.
- The heater in the HP borehole is similar in design but more powerful (1250 W, compared to 750 W) and the packer in the HP borehole has a sealing element ~2× longer, and the HP borehole apparatus is built entirely from stainless steel (Figure 6).

Figure 6. BATS HP packers; bottom: BATS 2 HP packer (in box), top: BATS 1 HP packer (in pipe).

By March 2024, five heating events have been conducted in the BATS-2 array (Figure 7). The heater tests have been conducted at different temperatures, to shed light on temperature-specific effects (e.g., temperature-dependent thermal conductivity and heat capacity – Sweet & McCreight, 1980).

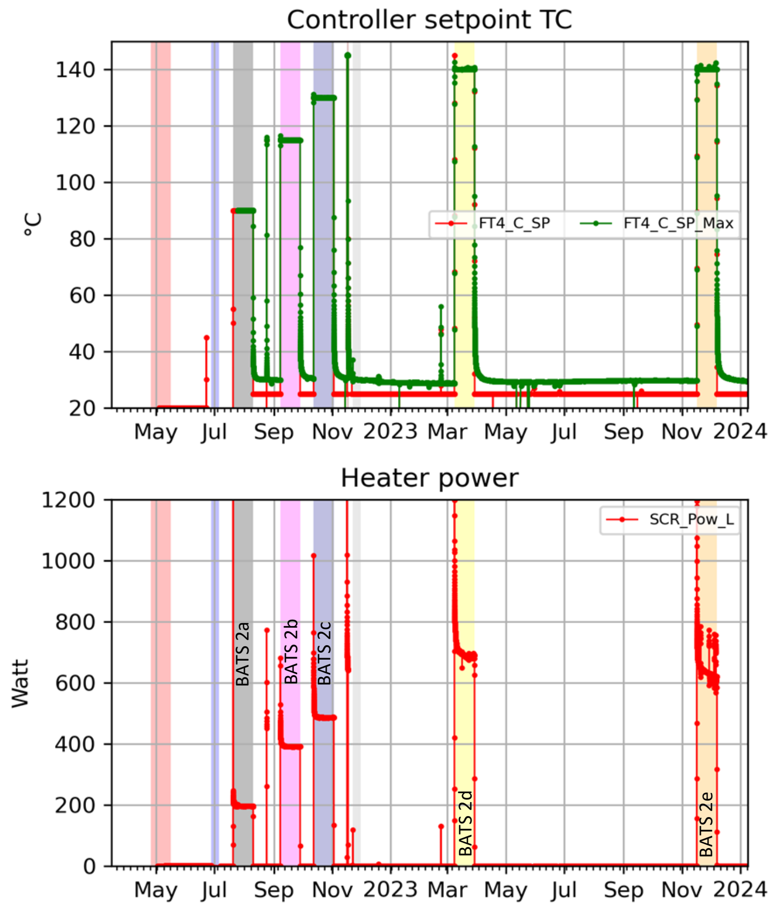


Figure 7. BATS-2 Heating events (a-e); top: applied setpoint temperature, bottom: resulting heater power.

Further heater tests in BATS 2 are planned later in 2024, possibly including:

1) Heater tests with a heating phase twice as long, to see if other effects become more important during longer heating cycles.
2) Heating with a slow reduction in heater power at the end of the test (rather than an abrupt termination), to determine the impact this has on the observed response.
3) Heating on a cyclical loading (square or sine wave) to determine the repeatability of the observations made over multiple heating cycles.

At the time of this writing (March 2024), the BATS 2 array is still in good condition, and will likely continue to be tested while plans for BATS 3 tests elsewhere in the WIPP underground are developed.

2.2 BATS 3 Proposed Investigations

BATS phase 3 (BATS 3) will involve tests and demonstrations seeking to isolate coupled THMC process effects observed in BATS 1 and BATS 2 tests and simulated in the DECOVALEX model validation exercise. BATS 3 will differ from BATS 1 and BATS 2 by using a strategy of parallel testing in smaller groups of boreholes, rather than a coordinated test with all simultaneous processes and observations instrumented together.

BATS 3 will focus both on several key experiments to test hypotheses or answer questions, but it will also require developing a few underground testing capabilities to make the required measurements. Brine availability (i.e., distribution of brine and the evolution of the EDZ) is still a key focus of BATS 3, but rather than coordinating two groups of 14 boreholes around a central heater, we will pursue individual or pairs of effects (e.g., permeability as a function of temperature, resistivity changes with brine content changes) in smaller groups of boreholes in greater detail. Most of the behaviors being monitored in salt are coupled together, making it difficult to separate tests into individual effects, but tests focusing on specific processes will be useful (although some repetition of monitoring may occur between tests). Individual tests will be model-driven, with clear pre-test conceptual and numerical models of expected behavior.

This more “modular” BATS 3 design will be located deeper into the WIPP SDI area (N-940 near E-540 is the current BATS 1/BATS 2 location). Moving BATS 3 to a more “out of the way” location will be beneficial to the test and ongoing WIPP operations. Independent tests will allow refinement and iteration on focused aspects of coupled processes in salt relevant to brine availability.

2.2.1 New BATS Infrastructure needed for Underground Research Laboratory

Based on experience gained from the shakedown test (Boukhalfa et al., 2018; 2019; Guiltinan et al. 2020), BATS 1, and BATS 2, building up a few key pieces of additional infrastructure, typically utilized at international underground research labs (URL) elsewhere would benefit the technical goals of the project, and allow easier coordination with any possible future testing efforts (e.g., possible WIPP geomechanical tests).

1. **Ground control** (i.e., mesh and bolting) and mine safety infrastructure could be expanded beyond its current extent into currently unused portions of the SDI area to increase the areas available for testing.
2. **Environmental enclosures** for personnel, computers, and certain sensitive equipment would make testing simpler and require less replacement of expensive equipment. Environmental enclosures provide temperature and dust control (e.g., conex or small shelter), which would significantly extend the life of measurement equipment in the underground, and possibly allow new measurements not currently possible in the underground.
3. **Power distribution system** to provide conditioned, reliable, monitored power with local battery backup (i.e., uninterruptable power supply – UPS). UPS located within an environmental enclosure would allow for long-term heating tests (with data collection) across power disturbances at WIPP.

4. **Network access** (i.e., data and phone) from an environmental enclosure to the surface would allow remote monitoring and contact with the experiments during possible reduced underground access.
5. **Flexible borehole drilling equipment** for constructing boreholes at the locations and orientations that make the most sense for the science or technical goals of the work. SFWST has already purchased a DIAMEC-260 drill, which needs to be incorporated into the M&O contractor system to be useful.
6. **Well-lit, lockable workspace** with
    a. Benches and V-head pipe stands to lay out horizontal packers and borehole tools for testing/inspection before installation or during troubleshooting.
    b. Space for limited field measurement and characterization of liquid and solid samples (e.g., pH meters, volumetric flasks, and balances).
    c. Ability to leak-test inflation and seal of packers underground (e.g., capped steel pipes), since packers must often be disassembled to get them into/out of the WIPP underground.
7. **Drift surveying and borehole logging tools** (survey and logging tools may also be rented or sub-contracted).
8. **Experimental-area wide EPA approval** for minor drilling/testing activities. Obtaining EPA approval for every small individual activity makes it difficult to get smaller tasks (e.g., drill a 5-m [16 ft] long, 10-cm [4 inch] diameter borehole in the SDI area) done on a schedule.

Some of this infrastructure could be funded by the DOE-NE SFWST Salt R&D program at Sandia, Los Alamos and Lawrence Berkeley national labs, and some may be provided in-kind by DOE CBFO (the site owner) through the M&O contractor (the site operator). Equipment or labor should be supported jointly between DOE-NE and CBFO, when appropriate.

2.3 Major Activities: BATS 3 Experiments

Several focused experiments are planned for conducting as part of BATS 3, including further investigation and refinement of aspects already tested as part of BATS 1 and 2. The experiments will be more flexible in their timing (i.e., they can be done concurrently or serially, depending on personnel and equipment availability). Due to the coupled nature of hydraulic and mechanical processes in salt, investigating processes also of interest to WIPP geomechanics is inevitable.

Each proposed experiment has a list of needed boreholes or other infrastructure, as well as a description of the science questions each experiment is designed to address (Table 1). This section is like—and supplemented by—the material presented in Appendix A of Kuhlman et al. (2017) for the initial BATS 1 tests.

This list of experiments is being proposed here for technical reasons, but the ultimate execution of each of them should consider the programmatic impact and financial constraints of the SFWST program.

These activities cover the major infrastructure expected for each test, but additional testing methods from BATS 1 and BATS 2 will likely be implemented (e.g., ERT, acoustic emissions, thermocouples), depending on expected test interactions.

The experiments summarized in the table are discussed in individual sections, where figures, more detail, and references are given. At the end of the section, a prioritization of experiments and testing methodologies is given.

Table 1. Proposed BATS 3 Experiments, Relevant Science Question, and Required Infrastructure

Test	Short Description	Science Question	Boreholes / Infrastructure
2.3.1 Long-Term Heated Borehole	Heating with N_2 circulation for longer period (multiple months).	Do brine inflow estimates (vs. BATS 1/2) change under longer times, more like repository-relevant time periods.	One 12-cm diam. 3.6-m long for heater One 5.3-cm diam. 5.5-m long for TC One 5.3-cm diam. 4.6-m long for sampling
2.3.2 Long-Term Heated Sealed Borehole	Heated interval without N_2 circulation.	Do brine inflow estimates (vs. BATS 1/2) change under repository-relevant borehole boundary conditions? Does increased borehole humidity significantly speed up borehole closure?	One 12-cm diam. 3.6-m long for heater One 5.3-cm diam. 5.5-m long for TC One 5.3-cm diam. 4.6-m long for sampling
2.3.3 Mine-by early observations of closure and damage	AE and fiber optic monitoring while drilling large-diameter borehole and make borehole/drift closure measurements for new openings.	How does damage (source of permeability and porosity) develop immediately after mining/drilling? Does monitoring while drilling or mining reveal processes not seen simply by pre- and post-monitoring?	Four 5.3-cm diam. 3-m long for AE sensor emplacement (removable) One 30.5-cm diam. 3-m long in middle of AE sensor boreholes to create damage
2.3.4 Historic test re-entry or sampling	Observation, sampling, or extraction of in-place WIPP experiments from 1980s	How useful are extended exposure tests, given their lack of monitoring for >30 years?	None initially, some drilling or overcoring may be required to access samples.
2.3.5 Epoxy EDZ Fractures	Epoxy or grout near-drift fractures via borehole, then drill- or mine-out salt to preserve damage. *Direct observation* of damage, which is EDZ in numerical models.	What is nature of damage around access drifts? How does it change with time and location (ribs vs. back vs. invert vs. corners vs. drift intersections)?	One small-diam. (~4.5 cm) short (<2.5 m) for injecting grout/epoxy into EDZ area of interest. Large-diameter (30.5-cm) core (or mining/saw) to remove salt with grout/epoxy filled cracks.
2.3.6 Long-Term Brine Inflow Sampling	Characterize brine composition and quantity from individual map units. There are few boreholes completed across single layers (not vertical or dipping).	What is variability in brine composition across map units at WIPP? Can provenance of observed waters be inferred from chemistry alone?	Multiple small-diam. (~4.5 cm) longer (> 6 m) for sampling with a slight downward dip (but stay in single layer). Space boreholes on a grid along a vertical profile, to see variability.
2.3.7 Seals & EBS	Emplace cast-in-place cementitious seals, testing the permeability of the salt/cement system with gas perm. Monitor seals for multiple years, removing some for destructive sampling/testing at intermediate times.	Can practical EBS system be developed with modern material and additives that provide demonstrably low permeabilities?	Several vertical or angled large-diameter (30.5-cm) boreholes (< 7 m) that have small-diameter (~4.5 cm) access-holes drilled at an angle to pressure test the gap under the seal. One seal may be co-located near a heater from 2.3.1 or 2.3.2.
2.3.8 Time-lapse	Monitor brine inflow to fresh boreholes with camera/light and acoustic emissions to make time-lapse showing brine migration.	How does the discrete nature of brine inflow (both space and time) influence its measurement? Are discrete acoustic emissions correlated with discrete brine inflow observations?	One 12-cm diam. 3.6-m long, with camera/light mounted near edge of EDZ.
2.3.9 DPC	Measure thermal response in salt around heated metal plate, which is pushed into EDZ with a "house jack" typically used to fix sagging floors.	How does a "large and hot" waste package change the thermal properties of the EDZ?	Mine a vertical notch (1 to 2 m wide) in a drift wall (could possibly work in a large borehole, but would require curved plates), insert a house jack horizontally with a heavy steel plate between the jack and the salt. Heat the plate, while monitoring temperatures around the plate with thermocouples in shallow (< 30 cm) very small-diameter (~6 mm) holes.
2.3.10 ERT with brine injection	Measure resistivity during brine injection into fractures.	How is brine migration controlled by the fracture distribution in the EDZ?	Multiple small-diam. (~4.5 cm) longer (> 6 m) for ERT instrumentation and brine injection.

2.3.1 Extended Heated Borehole with Gas Circulation

This experiment involves heating a borehole with circulating N_2 (like BATS 1/2), but for an extended period, possibly months to years. This would help explore how stable the production of brine from a single geologic layer without discrete clay layers is over longer periods of time. The heater tests in BATS 1 and 2 are shorter (less than a month), while some processes are slower and take longer heating periods to become important. Creep is sped up by heating but is still slow at relatively low deviatoric stresses seen in boreholes. Brine and gas migration occurs in fractures in the EDZ, the evolution of which can be quantified by repeated sonic velocity measurements around the heated borehole and correlated with accumulation of AE events. Fluid inclusion migration is also slow and may be a significant contributing factor to brine release after the end of heating.

In a future heat-generating waste repository, we expect waste-package decay heat to cause dryout and accelerated creep closure around the waste over years. This type of test may require investment in a battery backup UPS to maintain a constant heat source for months to years (i.e., across possible WIPP short-term power disruptions in the underground).

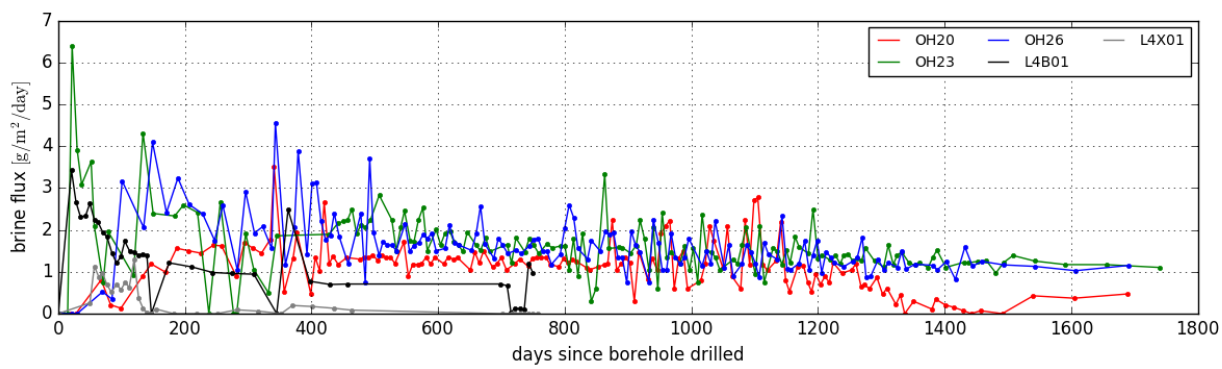


Figure 8. Long-term unheated brine inflow observation in WIPP horizontal boreholes (Kuhlman et al., 2017).

The results from this experiment would be compared to historical brine production from unheated horizontal boreholes at WIPP (Figure 8) and brine production from heater tests conducted in vertical boreholes at WIPP (Figure 9), which crossed clay layers and produced significant brine, this proposed test would create an environment more like what is expected in a real repository (i.e., long, sustained heating). This will help to predict the expected long-term brine production rate, rather than simply extrapolating from short brine production tests (BATS 1/2) or using brine production rates from longer tests that intersected clay layers (Rooms A/B).

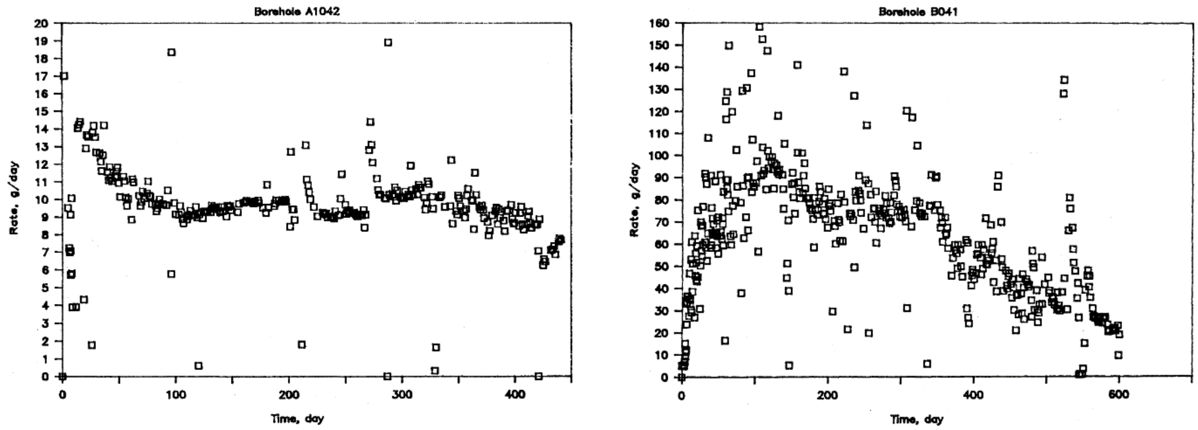


Figure 9. Brine produced in vertical boreholes during WIPP Room A (470-W) Room B (1500-W) heater tests (McTigue & Nowak, 1988).

The hypothesis being tested is that brine production in a salt layer (i.e., horizontal borehole that does not cross a clay or anhydrite layer) will eventually run out of brine to produce, given a long enough heating time.

The long-term heated borehole should be run for at least the same length of time as the sealed heater test for comparison between the two tests.

2.3.2 Extended Sealed Heated Borehole Experiment

This experiment involves heating a borehole for an extended period, but without N_2 circulation through the heated interval during the test; only removing water after the completion of cooling. A sealed heated test interval would be more like the conditions expected in an actual radioactive waste repository than like the BATS 1/BATS 2 conditions with forced circulation of dry gas. For this test, brine that flows into the borehole is only sampled at the end. Observations from the packer-isolated portion of the heated borehole would be limited to imaging, and passive measurements of air temperature, air pressure, and relative humidity (i.e., no significant samples removed from the packer-isolated heated interval). There may not be liquid brine pooling in the borehole, depending on the applied power and the borehole temperature.

Any sampling before, during, and after the heating would come from adjacent satellite boreholes. The total amount of water produced to the heated borehole, and the amount and types of minerals precipitated would be compared to the results of BATS 1 and BATS 2, where the water vapor was constantly removed during the test (i.e., different borehole boundary conditions). Other geophysical methods (e.g., ERT, sonic velocity, and AE) may be used to monitor this test in satellite boreholes to see what impact moisture in the borehole has on the system response. The distribution of moisture in the system may be very different, leading to different ERT observations of apparent resistivity. Borehole closure will be monitored in the heated borehole, which will help quantify how much faster borehole creep closure occurs; humidity is known to speed up salt creep (Van Sambeek, 2012). Sonic velocity measurements provide a measure of the degree of fracturing and AE monitoring estimates the location of the fractures and when they formed.

In the heated brine migration test conducted at Asse in the 1980s, two of the four heated borehole sites were sealed, while the other two of the heated borehole sites had gas circulated through them (Table 2). One of the two sealed sites (#3) developed a leak at 516 days and had N_2 gas circulated through it from that point on (Figure 10). These sealed boreholes were monitored until the test was completed (or until site 3 developed a leak), and these gas-phase observations were consistent with the brine found in the boreholes at the end of the test.

Table 2. Asse Heated Brine Inflow Test (Rothfuchs et al., 1988)

	Site 1	Site 2	Site 3	Site 4
Radioactive	No	No	Co-60 source	Co-60 source
Pressure build-up allowed	Yes	No	Yes	No
Continuous moisture stream collected	No	Yes	No (Yes after leak on day 516)	Yes

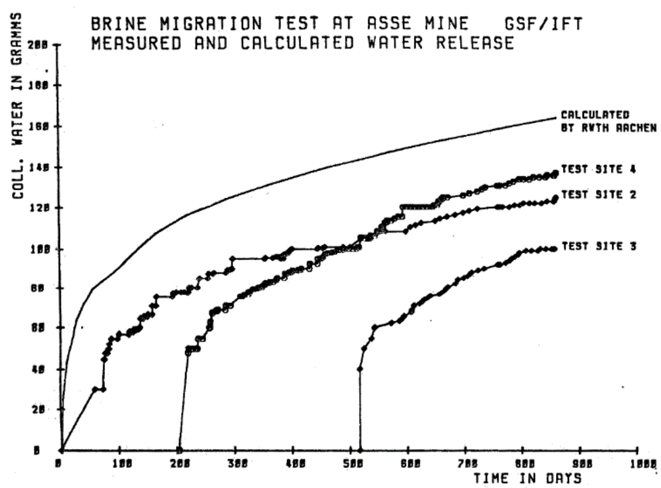


Figure 10. Asse Heater Test (Rothfuchs et al., 1988) Brine Production (not including sealed site #1).

In the Asse test brine production amounts were lower in sealed boreholes compared to unsealed boreholes (Rothfuchs et al., 1988). Brine production through time in the sealed boreholes was estimated from the total gas pressure and relative humidity measurements in the borehole (i.e., the water vapor partial pressure – assuming all water in the heated borehole was vapor). At site 1, gas pressure reached 3.21 bars [46 psi] absolute gas pressure during heating. Before the leak, site 3 reached 2.64 bars [38 psi] absolute gas pressure during heating. From comparing the results between the different sites, Rothfuchs et al. (1988) stated that vapor migration is the predominant moisture migration mechanism in Asse salt. They also estimated that Knudsen diffusion is more important than Darcy flow.

Compared to the tests conducted at Asse, this proposed test at WIPP would be different because the salt a Asse is approximately 10× drier than WIPP salt. This test would help to predict the reduction in brine production going from a dry, low-pressure heated borehole to a humid, higher-pressure heated borehole. The latter condition is more like what is expected in a repository, and the observations with different applied boundary conditions will help numerical modelers to validate their conceptual models regarding flow mechanisms in the salt.

The sealed borehole experiment could be run as long as needed (up to several months), but would need to be at least one month long for the effect of increased humidity and gas pressure in the heated borehole to have the largest impact.

2.3.3 Early Borehole and Drift Closure Methods

The mechanical closure of rooms and drifts has a strong influence on the extent and nature of the EDZ, whose permeability controls brine inflow. Current geomechanical models tend to underpredict room closure by roughly 2× during the first 50 days after a room is excavated (Reedlunn, 2018). This discrepancy may be related to how the stress around the room redistributes differently during single pass mining and multi-pass mining (Figure 11). It would be useful to compare the closure of two rooms/boreholes of the same final size but mined using different numbers of passes. A type of mine-by experiment (similar to Stormont et al., 1991) could be constructed, with instrumentation for monitoring early-time processes put in place before the drilling of the large central borehole.

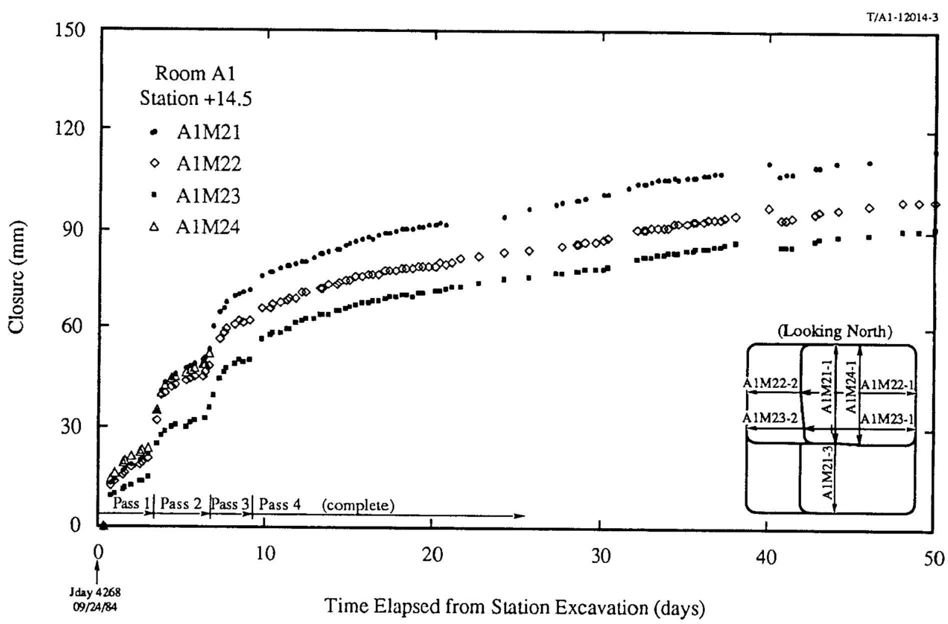


Figure 11. Early room closure measurements made during multi-pass mining of WIPP experimental area Room A1 (Munson et al., 1992).

3D laser scanning technology can be used to accurately measure the conditions of drifts and experimental areas (the equipment can be rented for demonstration), like a very dense traditional survey (Monsalve et al., 2019). Multiple scans can be conducted through time to quantify deformation – especially around a heated area where creep is faster. The method could be used to quantify areas with roof fall or other mechanical damage to better estimate volumes and sizes of impacted regions. The scans can also be used to document the exact position of man-made infrastructure (e.g., rock bolts or chain-link fencing; Singh et al., 2021), which may be included in some THMC or geophysical analyses.

The early onset of the EDZ around large-diameter boreholes could be monitored with fiber optic distributed strain and temperature sensing to observe displacements, as well as AE monitoring to map the discrete fracturing events that lead to damage. Distributed fiber optic strain and temperature sensing would be analogous to what was done in BATS 1 and BATS 2. AE monitoring would be analogous to the "seismic while drilling" technology used in the oilfield but applied to smaller boreholes and higher frequencies (AE vs. seismic). This type of monitoring could be conducted while drilling different a progressively larger series of boreholes (or larger boreholes around existing smaller boreholes, like multi-pass mining, above). The extent of the EDZ on the drift scale could be further assessed with the utilization of sonic velocity measurements. Herrick et al. (2009) showed that sonic velocity measurements correlated well with the density of fractures in extracted cores from the S-90 drift at WIPP, and that information was used to estimate the geometry of the EDZ. Since sonic velocities can also be correlated with the degree of fracturing in the salt, continued use of sonic velocity measurements could be used to assess how fracturing in the salt changes with time and heating/cooling cycles.

AE sensors, fiber optics, and stress sensors would be installed in boreholes before the start of drilling. Logistically, this test may require installing the AE sensors and fibers in boreholes completed from an adjacent drift (i.e., around a corner or pillar), to minimize interference between the AE monitoring equipment and drilling equipment. These data will also be useful for other geomechanical investigations (e.g., comparison of single and multi-pass mining) or structural mine monitoring at WIPP (Manthei & Plenkers, 2018). Significant AE observations might be correlated with the rapid damage accumulation and transient creep observed immediately after mining or drilling. Combining passive AE with active velocity measurements could give a greater understanding of the evolution of the EDZ. Located AE events track the migration of damage into the formation, while active velocity measurements would be used to monitor changes in elastic properties of the EDZ over time.

The hypothesis being tested is to determine if AE or pre-installed fiber optics can be used to characterize the significant early-time deformation and damage that occurs in salt. Monitoring of background noise can also be conducted in the drift, to improve understanding of the data and getting detailed timestamps on in-drift activities. Typically, this damage and rapid closure occurs before the drilling or mining equipment can "get out of the way", therefore it is almost impossible to measure. This was a focus at WIPP during the Thermal/Structural Interaction (TSI) tests conducted in the old WIPP experimental area (Figure 11).

This experiment would involve planning and instrumentation before drilling a large borehole or excavating a new drift but would be over soon after the drilling or mining event. This would not be a long experiment, possibly several weeks of work.

2.3.4 Re-entry of Old WIPP Experimental Areas

Many experiments were conducted in the WIPP underground in the late 1980s into early 1990s (Matalucci, 1987a; 1987b; Munson et al., 1992; 1997a). Kuhlman et al. (2012) presents a summary of most of the experiments undertaken at WIPP, and Figure 12 shows locations for most of these tests. During mining of the SDI area at WIPP, plans were prepared for re-entry or sampling of experiments left-in-place at WIPP (Brady et al., 2013).

Many of these drifts or rooms in the northern WIPP experimental area were abandoned with little reporting or documentation due to changes in DOE priorities and ground control or miner safety issues. Using first inexpensive flying drones or tethered robots with cameras (possibly followed by 3D laser-scanning), documentation of the condition of inaccessible areas could provide key datapoints related to the extent of roof falls, room closure, and brine inflow (e.g., salt stalactites and efflorescence) in unmaintained areas, without compromising worker safety. Such data could eventually help validate the approach used to recently simulate empty room collapse and reconsolidation at the WIPP (Reedlunn et al., 2019).

Seal elements are still in place, that were installed in the 1980s, and they could provide very useful engineered barrier system (EBS) data for exposure of seal materials for longer periods of time. Material exposure tests could also harvest invaluable data that currently exist in inaccessible areas at WIPP (e.g., analysis of waste package materials left in boreholes since 1980s).

The timing of this experiment depends on what level of investigation is completed, and how invasive it is. A simple scoping study with drones or robots to investigate the condition of these parts of WIPP would be relatively quick. A larger investigation would require more significant planning, with possible drilling or mining to collect samples.

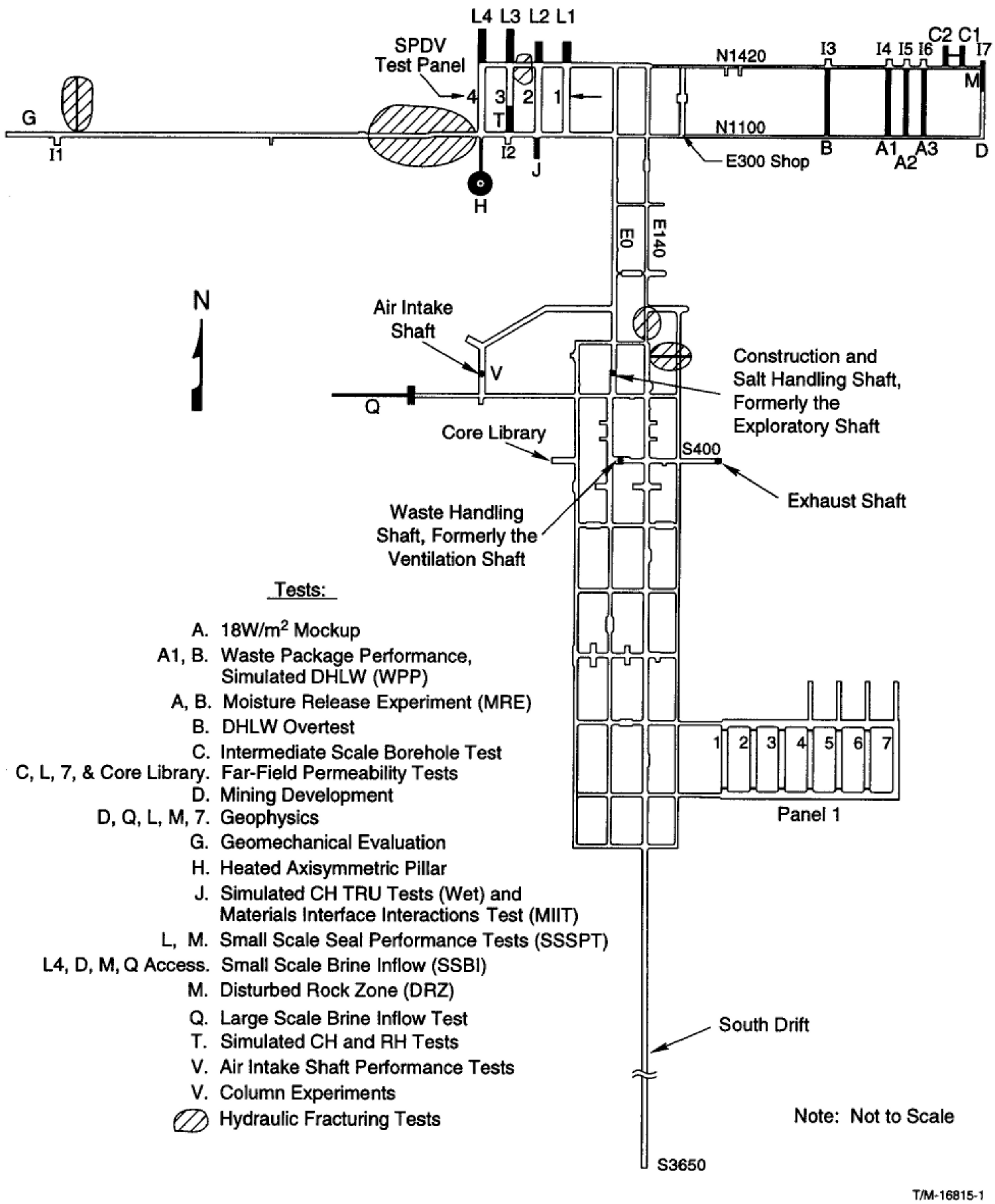


Figure 12. Historical WIPP test and Experimental Areas (Munson et al., 1997a).

2.3.5 Directly Preserve and Characterize EDZ Fracture Network

In the far-field, and after hundreds of years, there are no open fractures left due to creep closure and healing. Around the access drifts and boreholes, a heterogeneous and anisotropic excavation damaged zone (EDZ) exists (see examples of the nature of the EDZ in Figure 13) that varies with time. The EDZ is the pathway that allows to drifts and boreholes, and it is an important feature in performance assessment models. More information is needed regarding:

- The development and eventual healing of the EDZ around excavations – fractures in the EDZ accumulate and get larger with time (first few months), then eventually start to close and heal (years).
- The variability of the EDZ in space around an excavation (corners of square rooms, near drift intersections, in the wall vs. in the floor).

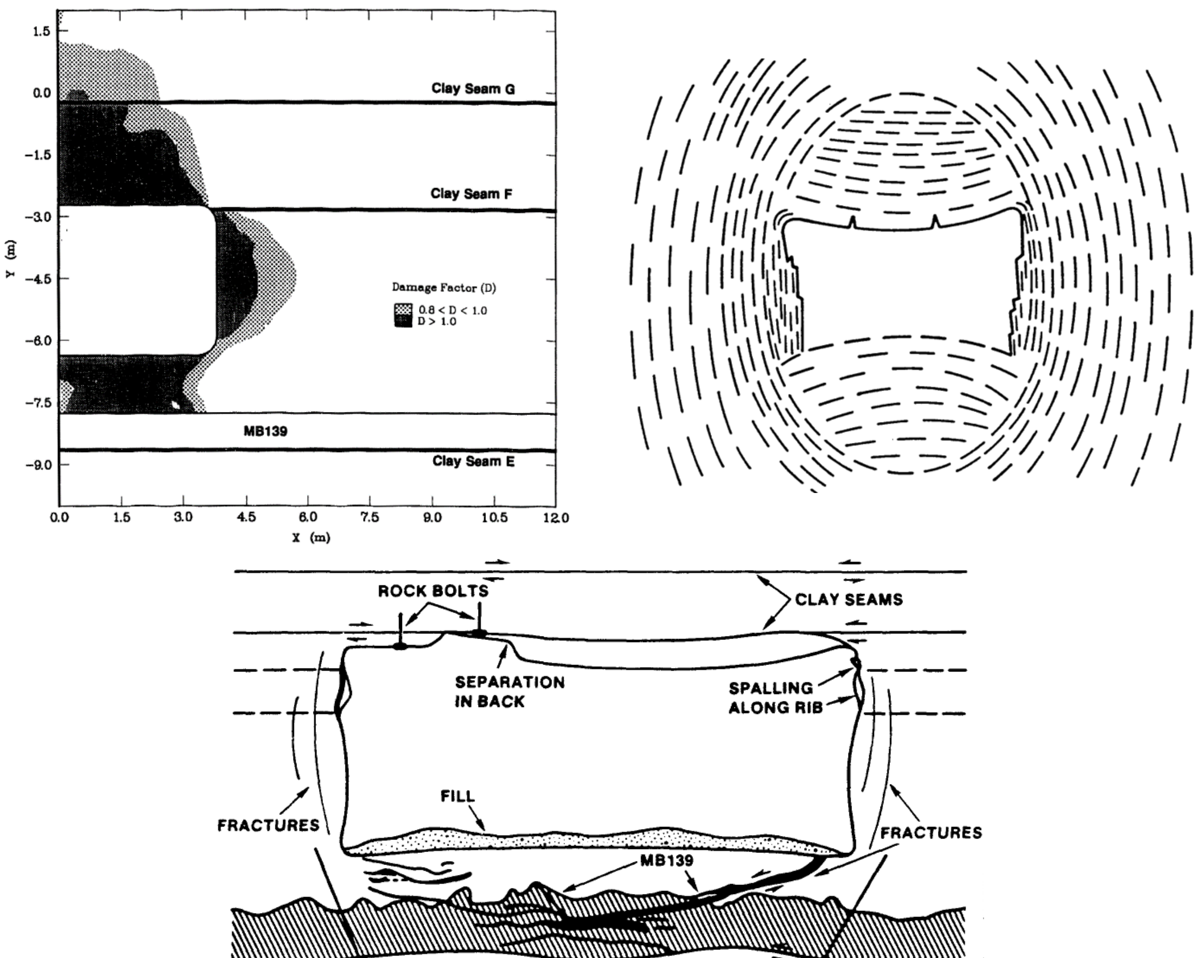


Figure 13. EDZ fractures. Upper left: Numerical modeling simulation of EDZ extent at WIPP (Van Sambeek et al., 1993), upper right: cartoon of observed EDZ fracture pattern at Asse (Borns & Stormont, 1988), bottom: cartoon of EDZ at WIPP (Borns & Stormont, 1988).

To characterize fracture networks more directly in the EDZ (rather than indirectly observing its effects on gas flow, brine flow, resistivity, or sonic velocity), we propose injecting colored epoxy or grout into portions of the near-drift EDZ fracture network, then over-coring or mining out the treated area. The effect of gravity on the flow of grout will have to be overcome by applied pressure (possibly behind a plug or mechanical packer). While it is possible to characterize micro-fracturing in salt cores (Hansen, 2003), it is difficult to characterize fractures in situ (but permeability or sonic velocity are indirect ways to do this), and cores cannot consistently sample macro-fractures, since cores come apart at large through-going fractures.

Preserved fractures in samples will be observed first non-destructively via X-ray CT scans and then destructively by dissolving away the salt after sampling. The process could be repeated through time and at different locations around the perimeter a room or drift (e.g., middle of wall, corners, floor or back). Information about the distribution, orientation, aperture, and evolution of fractures would be key for constraining flow models of processes in the EDZ (Figure 13).

This experiment would not require long observation periods (i.e., the time between the injection of the epoxy/grout and the extraction would be short), but it could be done multiple times and at different locations to characterize the change of distribution of fractures with space and time.

2.3.6 Long-Term Brine Inflow and Sampling Experiment

To better characterize the variation in brine availability due to fine-scale lithologic layers (i.e., amount of clay, polyhalite, or anhydrite), we propose a series of horizontal boreholes at different elevations, each long enough to sample the formation beyond the drift EDZ and completed in a single map unit. Boreholes will have a slight downward dip to collect brine at the far end of the borehole, will be sealed with a mechanical packer, and will be sampled for brine volume and composition sample at least weekly under ambient conditions for months (building on observations made historically at WIPP by the M&O contractor, Figure 14). Sponges will be used to soak up small amounts of brine, while ¼-inch stainless-steel tubing and a vacuum pump will be used to collect larger samples.

Brine chemistry is observed to vary between map units or marker beds. Major ionic species (e.g., $\mathrm{Na^+}$, $\mathrm{K^+}$, $\mathrm{Mg^{2+}}$, $\mathrm{Cl^-}$, $\mathrm{SO_4^{2-}}$) and minor ionic species (e.g., $\mathrm{Li^+}$, $\mathrm{Ca^{2+}}$, $\mathrm{Br^-}$, $\mathrm{BO_3^{3-}}$) have been observed to vary with spatial location, and with time in boreholes at WIPP due to changes depositional and in-place mineral alteration conditions (Stein & Krumhansl, 1988; Deal et al., 1995). Observations of brine production rate (i.e., quantity of brine through time) and samples for laboratory analysis of brine chemistry (i.e., composition of brine, including dissolved species and stable water isotopes) from a range of lithologic intervals can be used to quantify the variability in brine availability at the meter-scale at WIPP, and improve the inference of provenance (i.e., water source) from chemistry. This complements ongoing studies made on the water source from stable water isotopes.

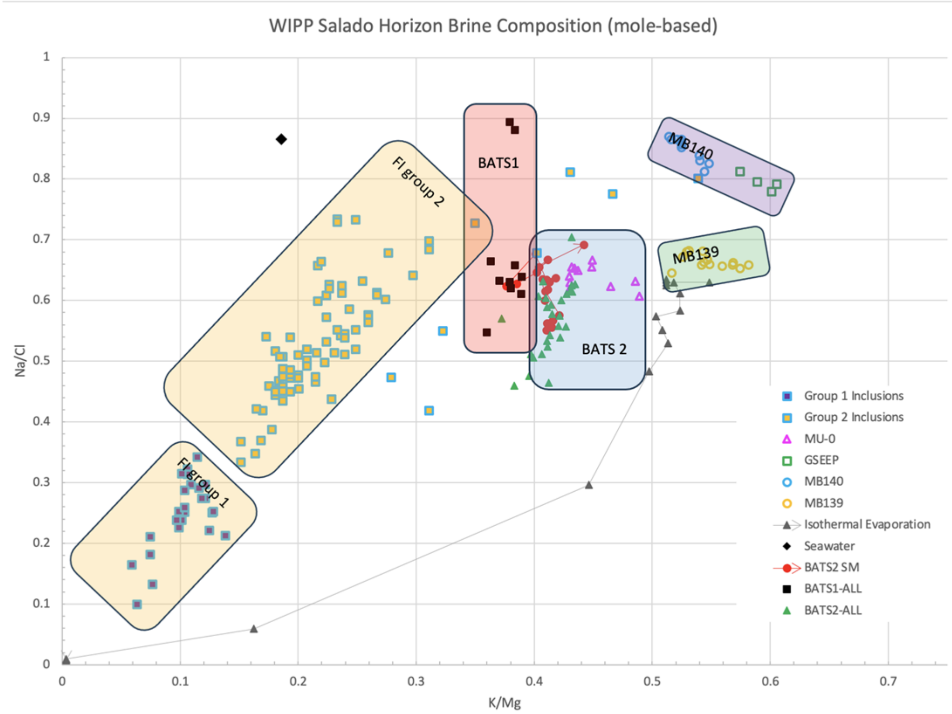


Figure 14. BATS 2 chemistry timeseries (red circles) plotted with historic fluid inclusions, BATS 1data (black squares), and WIPP historic brine MU-0, MB-139, and MB-140 (Kuhlman et al., 2023).

This would involve long-term monitoring of brine inflow into boreholes. Once the boreholes are drilled, the monitoring activity would not be a significant investment, but routinely monitoring it through time would be important, hopefully for multiple years (possibly at monthly intervals).

2.3.7 EBS/Seals Testing with Permeability Experiment

Based on the observations made in cement seals emplaced as part of BATS 1 and BATS 2, we will install, monitor, and sample different formulations of laboratory- and field-constructed cement plugs along with improved instrumentation. These smaller-scale engineered barrier system (EBS) seal tests (tens of cm to meter scale) would be a bridge to larger-scale (several meters) drift sealing demonstrations in subsequent years.

Some of the cement seals will have angled access boreholes to the interval behind them to allow permeability testing of seals at ambient and elevated temperatures (Figure 15). In this type of test, the intervals above (A) and below (B) the seal can be a permeable material like run-of-mine salt.

Seals can be allowed various levels of exposure to intact salt, brine, reconsolidating granular salt, and heat, to see the impact these components have on the performance of various seal components expected to be used in a salt repository. A significant small-scale plugging and sealing program existed at WIPP (e.g., Stormont, 1986), but the impacts of heat and brine were not a focus of that work, and the impacts from modern cement formulations or additives have not been tested (e.g., clays that swell in the presence of brine—palygorskite/attapulgite—rather than bentonite). Some of the historical components of cement may no longer be available or may be in short supply in the future (e.g., coal fly ash after phasing out coal power plants).

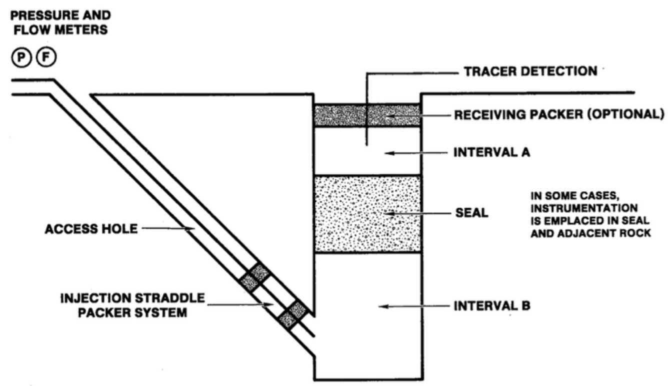


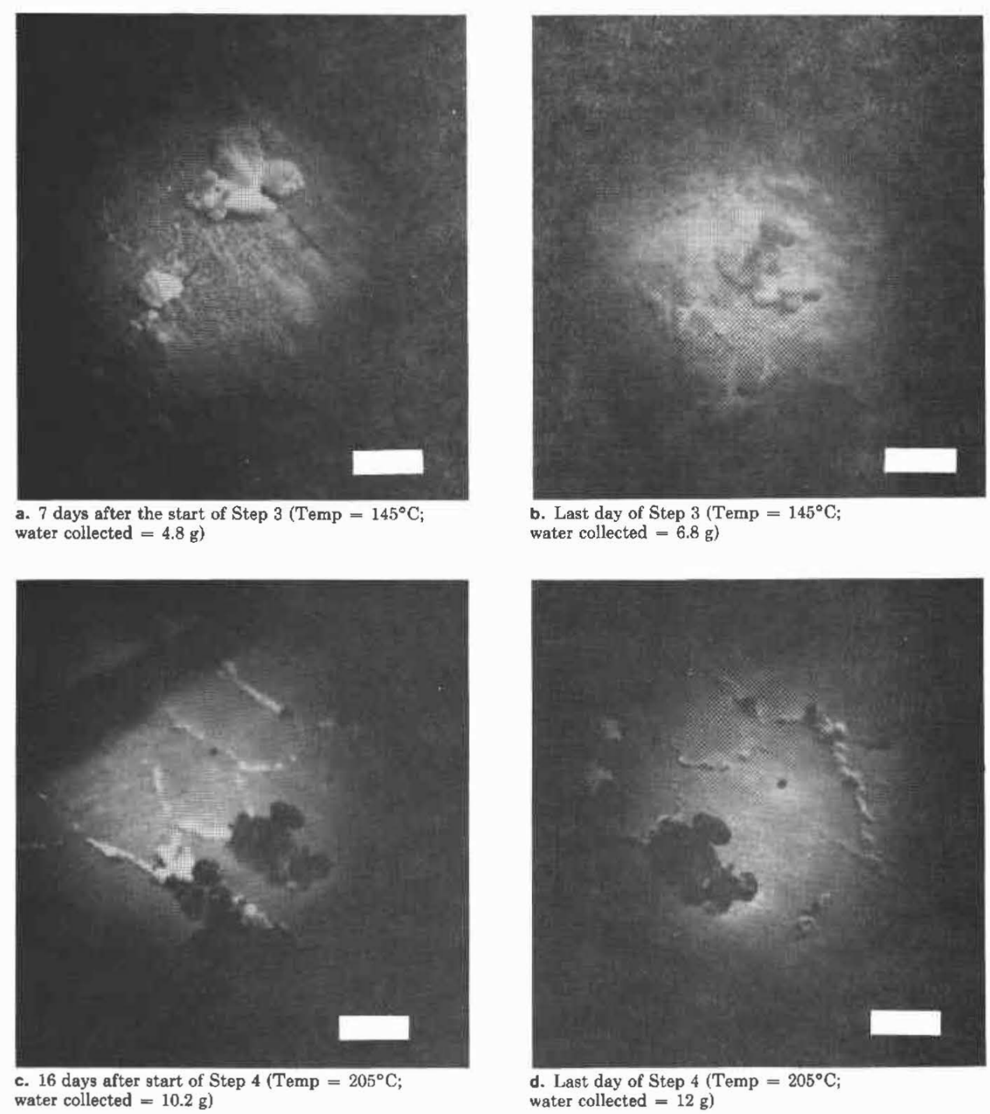
Figure 15. Typical configuration of a vertical borehole seal test with 30-degree access hole (Stormont, 1986).

Seals could be instrumented with both traditional strain gauges, stress gauges, and thermocouples, but also distributed fiber optics strain and temperature sensing (e.g., fiber optics coiled up inside seal to measure changes at many locations), to integrate small-scale changes over long distances.

The exposure tests of seal materials to typical WIPP brines (i.e., understanding the brines in the salt, as discussed in experiment 2.3.6) would benefit from multi-year exposure, with minimal monitoring during that time. Long-term repository design requires EBS materials to be compatible with the expected repository environment (e.g., stresses and formation fluids), and maintain their low permeability over their design lifetime. Possibly permeability tests would be conducted occasionally to confirm the performance of seal components. Post-test over-coring would also be useful, to see the condition of the seals materials in the laboratory (also see proposed re-entry activities).

2.3.8 Time-Lapse of Efflorescence and Stalactite Accumulation

Time lapse video will be collected in or adjacent to heated boreholes to monitor the time-evolution of efflorescence (i.e., "popcorn") or salt stalactites. These data would provide some unique documentation on to the discrete nature of brine flow in salt. Brine or vapor only flows between grains of salt and does not flow continuously in time but has been observed to flow in spurts – salt grains themselves are impermeable (Shefelbine, 1982). Time lapse video of precipitate in boreholes and fracture development around excavations could also be insightful (Figure 16), and hopefully the quality, resolution, and price of small, sealed camera technology has improved significantly in subsequent decades. These observations could be done as part of other experiments and would likely produce a highly visible product that would be good for program outreach efforts. Additionally, combining visible and infrared cameras together might produce more quantitative results. AE monitoring data could also be compared against brine inflow data, to see if there are correlations between the discrete mechanical popping sounds and discrete inflow of brine into boreholes.



a. 7 days after the start of Step 3 (Temp = 145°C; water collected = 4.8 g)

b. Last day of Step 3 (Temp = 145°C; water collected = 6.8 g)

c. 16 days after start of Step 4 (Temp = 205°C; water collected = 10.2 g)

d. Last day of Step 4 (Temp = 205°C; water collected = 12 g)

Figure 16. Monitoring growth of efflorescence in situ. Scale bar is ~0.5 cm (Shefelbine 1982).

Passive monitoring of brine inflow to an unheated borehole could occur for months to years after drilling of the borehole. Much of the brine will flow in at early times, so the most interesting period will likely be the first few weeks or months after drilling.

2.3.9 Experiments to Explore Effects of Large, Hot Waste Packages

An area of interest to DOE-NE is the quantification of any differences in repository evolution that may occur when disposing large (i.e., physically big and heavy), thermally hot waste packages in salt. Working towards improving this understanding, heated borehole experiments will explore impacts of higher-temperature heat sources (i.e., up to 200 °C) combined with applied stress, to contribute to understanding of possible waste package buoyancy effects in long-term simulations (Clayton et al., 2013). A heated metal plate may be mechanically or hydraulically pressed against a borehole wall or drift wall/floor with variable amounts of force, to observe the thermo-mechanical effects, including how the presence of heat, humidity, and brine facilitates accelerated creep under these circumstances.

The EDZ near the drift has higher porosity and has directional fractures (Figure 13), therefore the near-drift thermal conductivity is expected to be lower and anisotropic. This test would monitor the thermal conductivity in such a region, and observe whether a large, hot, heavy waste package might quickly heal the damage, and increase the thermal conductivity of the salt (to overcome the reduction in thermal conductivity of salt due to increased temperatures).

Another possible configuration for a in situ heated and loaded test is the "corejacking" test (Figure 17) conducted at Avery Island by RESPEC (Van Sambeek, 1981; Sickney & Van Sambeek, 1984). This test measured closure of the inner borehole through time, while the outer annulus is loaded with curved flatjacks (i.e., corejacks) and heaters in vertical boreholes around the corejacks allowed conducting the test at elevated temperatures.

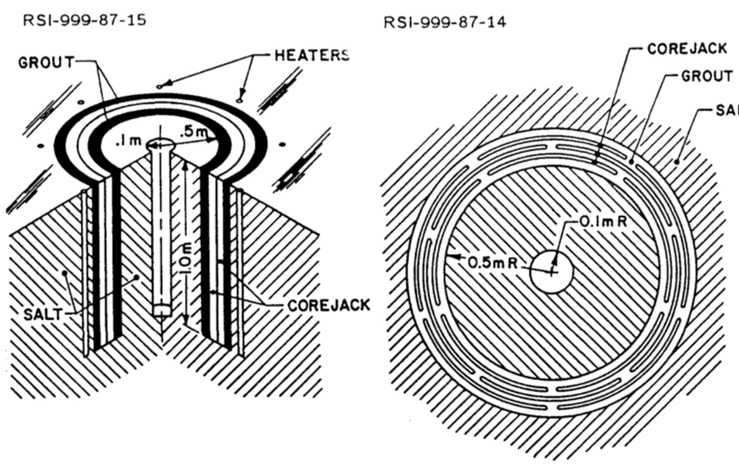


Figure 17. Corejacking configuration for externally loading a cylinder of salt in situ while heating (Stickney & Van Sambeek, 1984).

The impacts of strain at low deviatoric stress may be important to interpreting these types of experiments. Observations of small strains in the far-field around a loaded area could be accomplished with fiber optic measurements (like performed in BATS 1 and BATS 2). These measurements may be able to observe that are otherwise difficult to observe (Bérest et al., 2019).

These focused smaller-scale experiments could be a bridge to follow-on drift-scale demonstrations of large, hot waste packages.

These experiments may require extended monitoring (weeks to months), depending on the loading and heating rates applied.

2.3.10 Electrical Resistivity Tomography (ERT) with Brine Injection

Similar to the ADDIGAS test performed in the damaged salt in the floor at Asse (Jockwer & Wieczorek, 2008), this would use an ERT system to map the flow of brine with tracers, injected into boreholes (Figure 18).

During BATS 1 and BATS 2, observations were made of brine migration using ERT (Wang et al., 2023), but the observations were mostly passive, only controlling the brine content indirectly by heating and cooling the salt. This experiment would more directly add brine to fractures to map its migration, possibly with brine sampling during the test, or post-test coring. The brine could include dissolved tracers (e.g., rare anionic metals like perrhenate or fluorescent dyes) to facilitate the observation of the brine in boreholes or core samples. With the advancement of ERT hardware and data processing algorithms, high resolution ERT monitoring can closely track the distribution of injected brine in salt, allowing the mapping of fracture and permeability distributions in the formation.

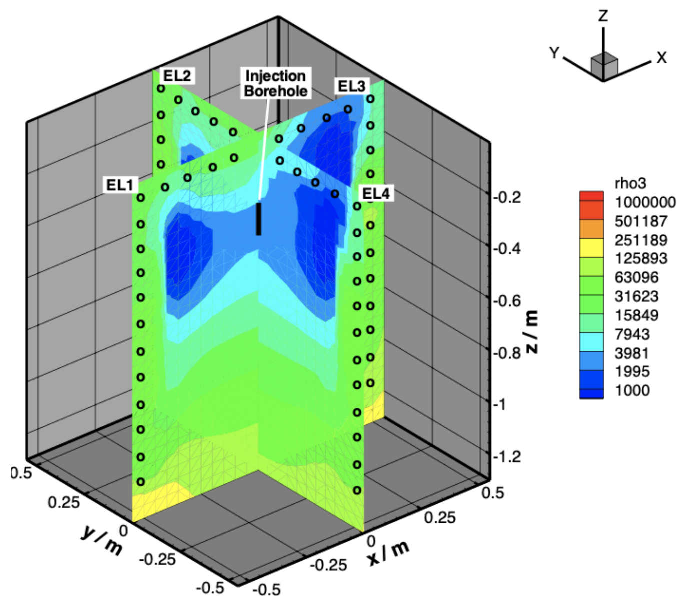


Figure 18. Interpreted resistivity from ERT during brine injection in salt at Asse (ADDIGAS; Jockwer & Wieczorek, 2008).

This type of injection experiment would be useful for mapping out fractures and can safely be done away from activities seeking to measure natural brine production from the salt.

ERT could also be monitored in the floor of a newly mined drift, to monitor the accumulation of brine in vertical boreholes (Deal et al., 1995). It is well known that vertical boreholes in the floor of drifts tend to fill with brine over time (i.e., the damage below the room is acting like a sump for brine flowing into the EDZ of the drift). This could be a passive way to monitor this brine accumulation, by conducting ERT surveys periodically (e.g., once a week).

An active brine injection experiment might only take a few weeks, but a passive brine accumulation test may take several years. The monitoring frequency would be less in a long-term test, while the monitoring frequency in an active test would be higher.

2.4 Major Activities: BATS 3 Tool and Method Development

The experiments in the previous section could be better instrumented with certain tool and method development efforts, typical of an underground research laboratory. Some of these capabilities existed once at WIPP (or other salt URLs, like Asse) but require re-development to get working again (Table 3). Re-implementing (but with improved modern technologies) is seen to be an important part of the URL development and overall disposal program continuity effort. These would be tools and method developments capable of measurements that would be needed to be made at a new URL or repository in salt, so it would be expedient to have these capabilities ready for when they are needed. In Table 3, TRL stands for technical readiness level, a numerical scale ranging from 1 to 10, indicating maturity of a technology. TRL 1 is the lowest level (i.e., development of principles and concepts), while TRL 9 is the highest level (i.e., flight-proven in mission operations).

Table 3. BATS 3 Tool and Method Development Opportunities

Tool	TRL	Short Description	Technology Question	Infrastructure
2.4.1 Brine Pressure/Permeability Measurements	1-2	Brine pressure and permeability testing of intact salt using short intervals of boreholes using double-packer systems.	Can we accurately measure salt brine permeability (main quantity of interest), given the effects of tool/interval compressibility and the complexity of salt/brine interactions?	Dual packer brine pressure and permeability testing system
2.4.2 Rock Stress Measurements	3-4	Rock stress measurements around excavations and boreholes to validate numerical models	Can we measure changes in stress during 1) drift closure, 2) borehole heating, to validate numerical models?	Sets of directional pressure plates either hydraulically jacked against borehole wall or grouted into place.
2.4.3 Gas Permeability Measurements	4-5	Gas permeability testing of EDZ in short intervals of boreholes using multi-packer systems.	Can we accurately map EDZ distribution using gas permeability tests, which are easier to conduct than brine permeability, but interpretation must deal with two-phase flow?	Develop multi-packer gas testing setup for typical borehole diameter expected (5.3 cm or 12 cm).
2.4.4 Chemistry Measurements	1-3	In situ and in-drift geochemical measurements to make some decisions in field	Can we bring new technology (e.g., robust field sensors, hand-held XRF) to create a monitoring breakthrough?	Develop capability to estimate brine composition in boreholes or in the field, to allow some decisions to be made with real-time data.
2.4.5 Sonic Velocity Measurements	4-5	Measure sonic velocity within and between boreholes to map EDZ.	Can the EDZ be efficiently mapped out with non-invasive sonic velocity tool?	Develop sonic velocity tool to characterize boreholes drilled for other tests.
2.4.6 Large Sample Collection	2	Develop approach for collecting large intact samples of salt for laboratory testing	What approaches can be used to extract large (~1 m) size rectangular or cylindrical samples safely and efficiently without excess damage?	Develop saws or drills that can be used to extract large salt samples safely and effectively with minimal damage.

BATS 1 and BATS 2 have led to the development of several methods. The geophysical methods of ERT and fiber optic have already proved their usefulness, and now are already part of experiments listed in the previous section. BATS 1 and 2 have also proved the utility of stable water isotopes and mass spectrometry to analyze the gas stream in the heated borehole. Most of the methods listed here were originally proposed to be part of BATS 1 or BATS 2 but were cut due to lack of budget or time to develop multiple approaches at once. Some of these tools could be used immediately with the experiments proposed in the previous section, while other of these tools would be used in future experiments.

2.4.1 Brine Pressure and Permeability Measurements (Intact Salt Characterization Method)

Measurements of brine pressure or mechanical stress in the salt would be useful for constraining coupled numerical models of brine production and thermal-hydrological-mechanical processes. These measurements may be done in profiles around an access drift or could be located near other heater tests (e.g., the sealed heated borehole). Static formation pressure and brine permeability can be measured in a brine- or oil-filled packer-isolated borehole interval (Cosenza et al., 1999; Roberts et al., 1999; Beauheim & Roberts, 2002). These data will be useful for integration of efforts between BATS and possible additional geomechanical investigations going on at WIPP.

Measurement of formation fluid pressure or brine permeability is difficult, because of the extremely low permeability of the un-damaged formation, requiring sophisticated equipment (e.g., Figure 19) to be developed to make accurate measurements (Beauhiem & Roberts, 2002). Fluid pressure, temperature, and borehole distortion (using linear variable displacement transducers—LVDTs) must all be measured at multiple places, and the tests often were very long to ensure the stability and representativeness of the response (Figure 20 shows a ~300 day hydraulic test).

With this setup, Beauheim & Roberts (2002) showed the far-field static formation pressure at WIPP is essentially equal to the lithostatic stress (a key finding). The brine permeability methods showed the permeability of different layers in the salt does not correlate well with distance from the excavation (as the EDZ permeability does). This shows that the salt has low permeability outside the EDZ, and this was a key finding for performance assessment models.

This capability would be critical to have at a new site for characterization efforts, but would require significant development of equipment and expertise. Brine-based permeability measurements in evaporites are difficult to make. The technical readiness level (TRL) for this method would be low (1-2) at this point.

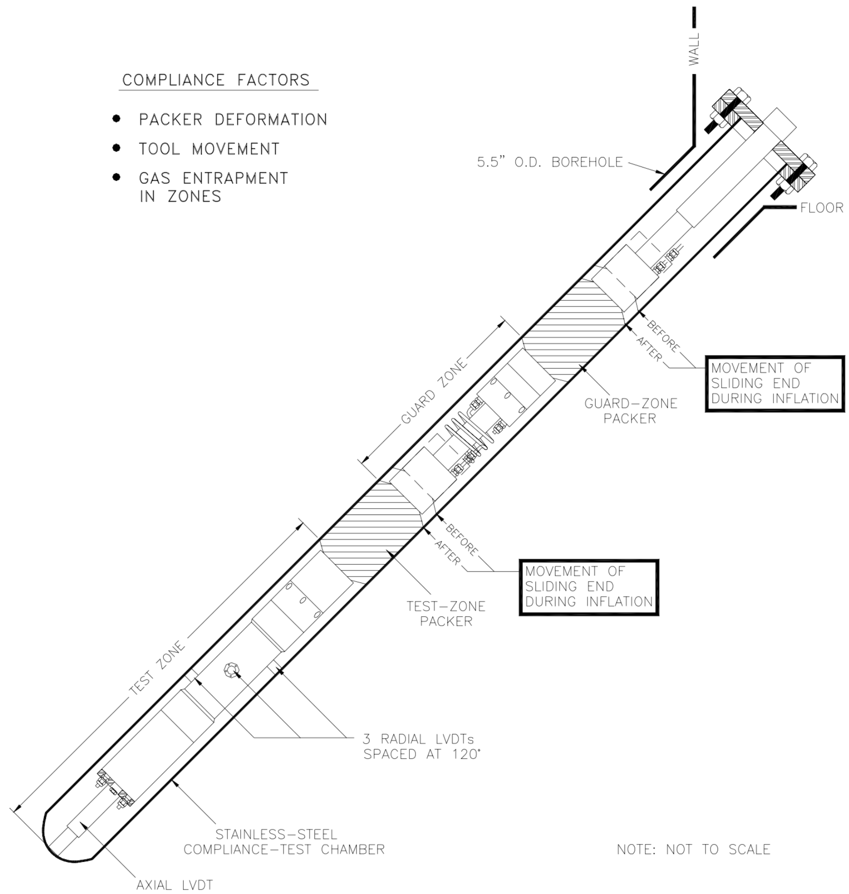


Figure 19. Typical double-packer system used by Roberts et al. (1999) to test brine permeability and formation pressure at WIPP. Compliance factors to consider during testing are noted.

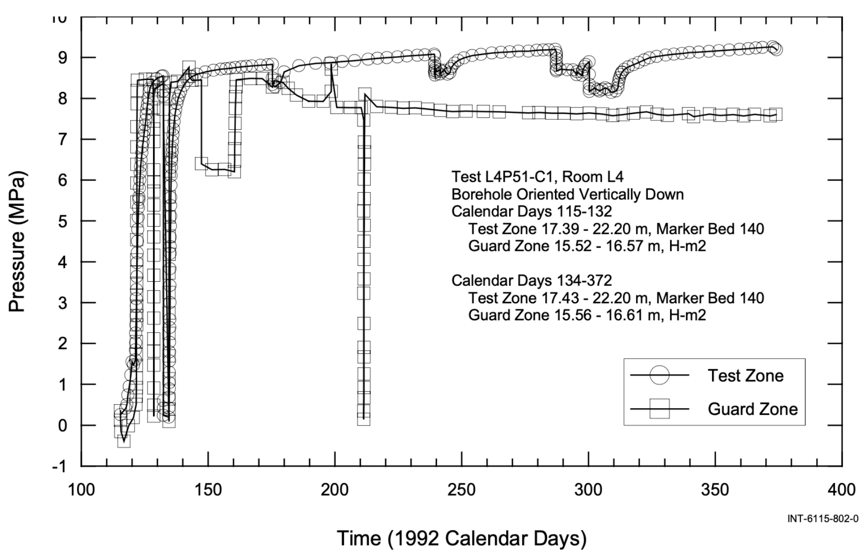


Figure 20. Example brine permeability and formation pressure testing sequence for MB-140 interval (Roberts et al., 1999).

2.4.2 Rock Stress Measurements

Directional rock stress measurements through time are difficult to make in salt but would provide key data for validating and confirming numerical models of thermal-mechanical processes. Stress gauges may be either hydraulically jacked against the salt in a large-diameter borehole or grouted into smaller-diameter boreholes. The different components of stress should be monitored around excavations (before, during and after mining or drilling), or around heated regions (before, during, and after heating). The main approaches for in situ rock stress measurement (Amadei & Stephansson, 1997) are:

1) directional pressure-plate measurements,
2) over-coring or strain recovery techniques,
3) hydrofracture and borehole deformation methods, and
4) inversion of non-linear stress-dependent memory effects.

Flatjack and pressure-cell methods are conceptually simple and direct but can sometimes be difficult to implement in the field. Strain recovery and hydrofracture methods are useful for site characterization efforts (Serata & Kikuchi, 1986), but they are destructive and cannot measure changes in stress through time at a single location. Non-linear stress-dependent memory effects depend on the constitutive model and can be difficult to interpret (Filimonov et al., 2001).

Rock stress measurements in soft rocks that creep (i.e., salt) are more difficult to execute (Corthésy & Gil, 1990; Corthésy et al., 2003), but in these rocks stress measurements through time are quite useful for numerical modeling validation, since the rocks have such dynamic behavior.

Installation of pressure plates via grouting into boreholes is a simple method for measuring stress and make a good candidate for a first approach. Other, more complex methods may be tried for comparison, especially if they can be coupled with other testing approaches (e.g., brine permeability testing or coring of boreholes).

Rock stress measurements would be very useful to augment existing and planned experiments, and given the diversity of available approaches, would be less difficult to get working. The TRL for this method would be approximately 3-4.

2.4.3 Gas Permeability Measurement (EDZ Characterization Method)

The permeability of the salt is a key aspect of brine availability (i.e., how brine flows to an excavation). Permeability testing in salt is difficult because the undisturbed salt is impermeable. The fractures of the EDZ associated with the access drift and boreholes provide the observed permeability. Additional refinements in gas permeability testing equipment and procedures (e.g., multiple-packer setups with guard zones) will be tested under ambient and heated conditions to better understand the distribution of damage and permeability in the salt, and how this damage is impacted by thermal expansion stress changes, relevant to brine availability around heated waste (Stickney & Van Sambeek, 1984; Stormont et al., 1987; Kuhlman & Malama, 2013).

Stormont (1988) presented the multi-packer gas permeability testing device used to characterize the EDZ in multiple boreholes at different orientations around a drift (Figure 21).

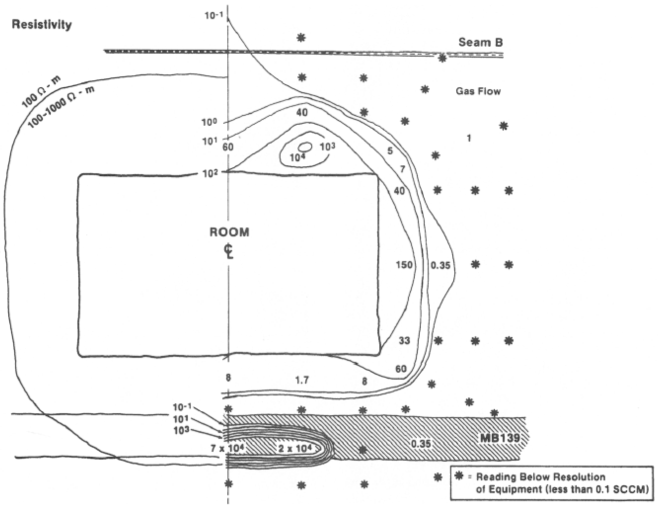


Figure 21. Results of interval gas permeability testing by Borns & Stormont (1988). Contours on right are mass flowrate of gas at a specified pressure. Left half illustrates observed resistivity around drifts.

An example of the configuration and plumbing of a multi-packer system for gas permeability testing is shown in Figure 22. A two- or three-packer system could be constructed in an analogous manner. Many "guard" regions are useful in testing low-permeability materials, since the pressure in guard intervals can be checked to ensure there is no leakage around one or more of the packers, improving the quality of the data.

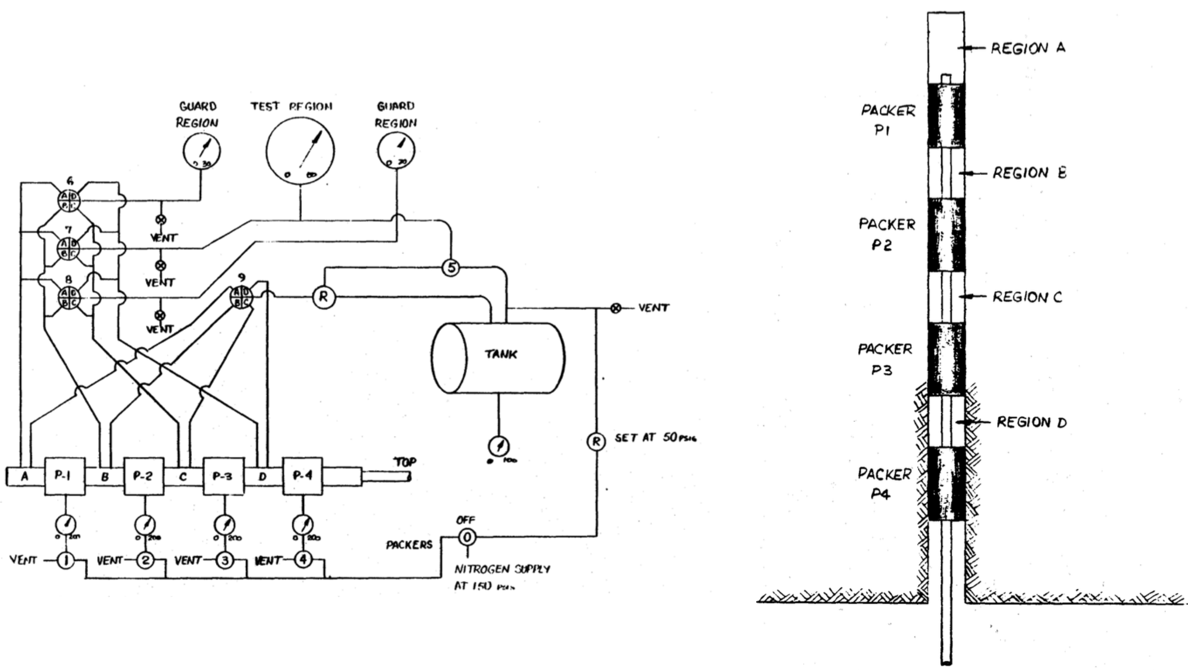


Figure 22. Multi-packer gas permeability testing tool developed for characterizing salt EDZ (Stormont, 1988).

Gas permeability measurements are already made in the D boreholes as part of BATS 2, but these packers are fixed, and only pressure decay tests are conducted. This would mostly involve making a tool that would allow rapid characterization of boreholes drilled for other experiments and include constant pressure flowrate tests along with the pressure decay tests for versatility. The technical readiness level for this method is 4-5.

2.4.4 In-Drift and In Situ Chemistry Methods

Brine composition and water isotopic makeup are key indicators of water provenance (i.e., source), and therefore a key component of brine availability (i.e., determining if brine is from fluid inclusions, clay pore water, or hydrous minerals). Measuring pH, alkalinity, electrical conductivity, and density of the complex brines encountered at WIPP is non-trivial, and requires specialized equipment, sampling methods, and analysis approaches. While the standard is to collect enough sample to bring this back to the laboratory for analysis, some tests (e.g., sealed heater test – 2.3.2) would benefit from in situ observations. Recent advances in technology have possibly brought in situ measurements of brine composition into the realm of the possible. We will explore several portable (i.e., in-drift) and in situ (i.e., in-borehole) possibilities:

1. **Portable X-ray fluorescence (XRF):** hand-held XRF instruments are improving in capability and reducing in price. This instrument can quantify elemental concentrations but doesn't work as well for elements with low atomic number. While they are not small or robust enough to place into a borehole, they would be useful for in-drift monitoring of salt composition and fluid chemistry (Swanhart et al., 2014; Kipnis et al., 2020; Gul & van Oort, 2021; Knight et al., 2021).
2. **Portable density measurements**: fluid density can be related back to ion concentration (Bernau et al., 2023), or at least ionic strength, if a robust equation of state exists for the composition. A combination of fluid properties could be measured to better constrain the composition (e.g., thermal conductivity, sonic velocity, density, or viscosity), but this approach would require site-specific calibration, and most of these instruments would not be possible to use inside a borehole.
3. **Portable or in situ light refractometry**: the refractive index for light through a transparent fluid can be related back to the ionic strength. The main benefit of this approach is that it could be done at the end of a long fiber optic cable (Khotiaintsev et al., 2012; Li et al., 2023). The sensor end would either be a glass hemisphere, or possibly a bent fiber optic cable (Maykut & Light, 1995). This approach could be used behind a packer, to measure brine composition (assuming enough liquid brine exists to cover the sensor).
4. **Portable or in situ Raman spectroscopy**: like the XRF, advances in technology have reduced the size and cost of this hand-held instrument significantly. The method has also been proposed to characterize strong brines or salts on interplanetary missions (Mason & Elwood Madden, 2022; Hughes et al., 2023). The main limitation of this method is that it is primarily sensitive to bond vibrations, so it would work best for ionic species like sulfate (SO_4^{2-}) and borate (BO_3^{3-}), but there is some reported sensitivity of the method to OH^- (which could be related to brine pH or complexation associated with the ionic strength of monatomic species – Fontana et al., 2013). Another benefit of the Raman approach is that it is based on infrared light, so it could also be conducted through a fiber

optic cable in a discrete or distributed sense (Li & Zhang, 2022), and therefore potentially used in a sealed borehole test.

These methods can be first tested in the laboratory on synthetic brines, to be compared against standard laboratory analyses or calibrated against relevant brine compositions. The usefulness of the method in the field is then the key second phase, since the environment of a salt mine can be damaging to sensitive electronics.

Given the variety of approaches, it may be possible to get something working quickly for measurement of brine chemistry behind a packer as part of BATS 3 heater experiments. Depending on what aspects of brine chemistry need to be monitored, this may be relatively low TRL (methods with some development required, like refractometery) or the TRL may be higher for methods that already have a hand-held unit available (Raman, density, and XRF).

2.4.5 Sonic Velocity Measurement Methods

Active AE measurements, rather than passive ones, can be used to indirectly interrogate the extent of the EDZ. These have been used in the past in horizontal boreholes in the Room Q access drift (Holcomb et al., 2001) and to observe the creation of an EDZ after mining (Holcomb, 1987). Active measurements involve "pinging" the salt and measuring the response a fixed distance away to estimate a velocity (Figure 23). The piezoelectric crystals were pushed against the borehole wall using a hand-pump hydraulic system.

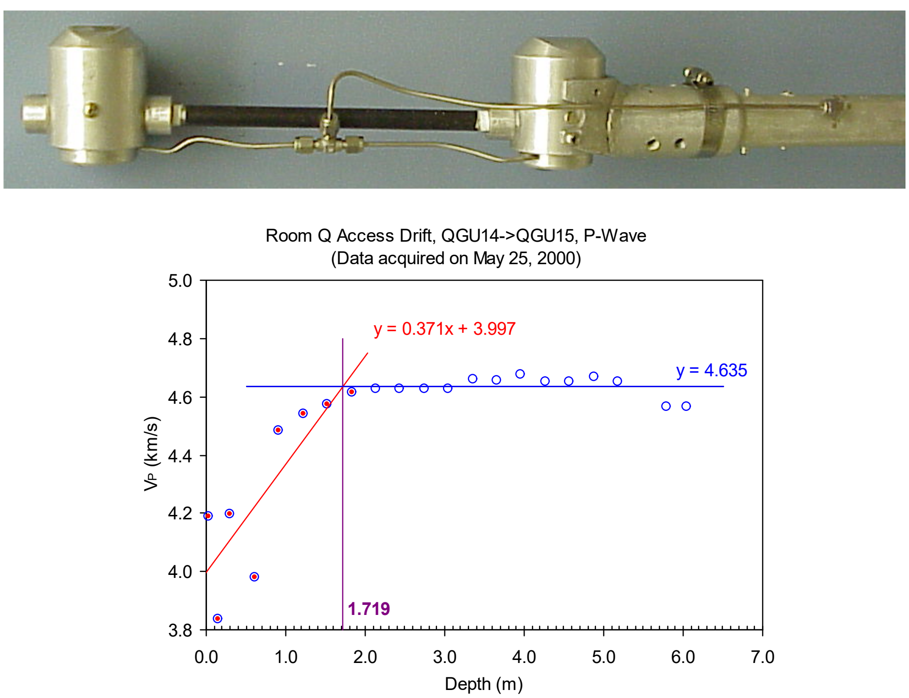


Figure 23. Sonic velocity system. Top: single-borehole tool, bottom: illustration of using P-wave velocity to estimate the extent of the EDZ (Holcomb et al., 2001).

This sonic velocity tool, if re-created with modern electronics, could be used with gas permeability straddle packers to estimate the extent of the EDZ in boreholes before other tests are conducted. This method could be used both during and before/after heating and cooling cycles because velocities will change due to damage, temperature changes, and possibly due to brine migration. AE sensors may be co-located with the sonic velocity instrumentation system, and the AE system may be used to monitor during sonic velocity testing.

This method has already been proven at WIPP, and could be re-built using relatively straightforward updates of older equipment with modern equivalents. This approach could be used to characterize boreholes drilled for other BATS experiments, and has a relatively high TRL, approximately 4-5.

2.4.6 Large Sample Collection

The ability to collect large samples of salt would be a capability that allows more realistic laboratory testing (Figure 24). Most cores collected from WIPP are ~10 cm [4 in] diameter. The largest-diameter cores collected recently at WIPP are 30 cm [12 in] diameter. The ability to collect approximately 1-meter salt samples would benefit multiple experimental programs. These could be collected with large-diameter drill bits, a series of overlapping smaller-diameter boreholes, or a rock or concrete chainsaw (i.e., a tool to cut deep, straight cuts).

For example, the "Salt Block II" heater experiment was conducted at Sandia using a 1-m diameter cylindrical sample, 1 m tall (Figure 25). The cylinder was machined from a larger rectangular block of salt (Hohlfelder, 1980). The dataset from this test was recently used to validate conceptual and numerical models (Tounsi et al., 2023). The dataset is useful, despite its age, since the large block-scale test is both large enough physically to be a representative volume, while being well-controlled and well-instrumented (which is more difficult to do in the field).

Figure 24. Example of large salt sample collected from Grand Saline Salt Dome (Serata & Gloyna, 1959).

One challenge with large sample collection is handling and transporting it, while imparting minimal damage to the sample.

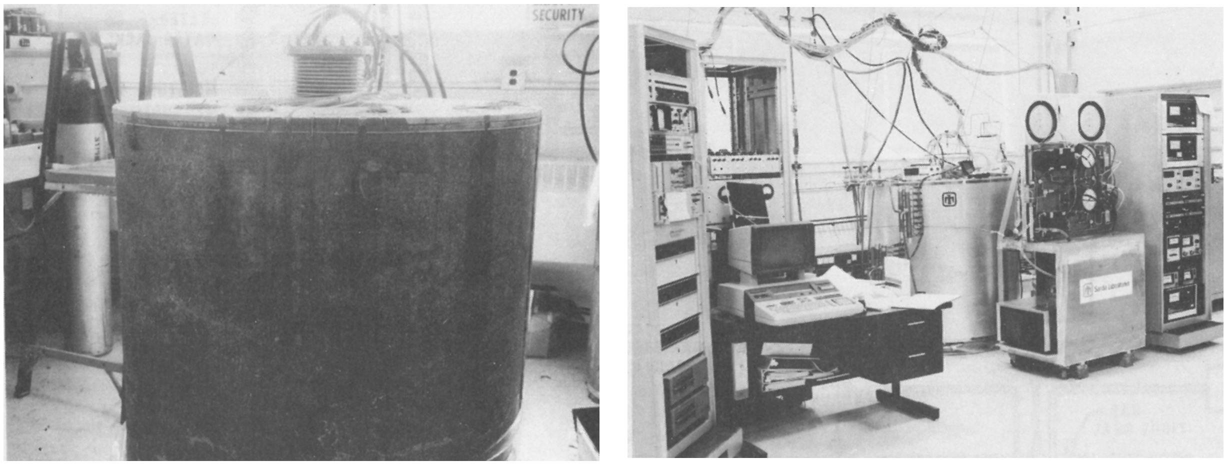


Figure 25. Salt Block II Experiments. Left: 1 m × 1 m cylindrical sample from Mississippi Chemical Company potash mine in Carlsbad before placement in enclosure, right: final experimental setup (Hohlfelder, 1980).

Obtaining large-scale laboratory samples requires both technical and logistical/safety hurdles. This approach might have a TRL of 2, but this could be increased with some consultation with WIPP facilities or operations personnel from other mines.

2.5 BATS 3 Summary and Prioritization

As was previously stated, brine availability concerns the distribution of brine, and how it flows to the excavation. The distribution of different reservoirs of brine is characterized through subtle differences is water isotopes and brine chemistry. The permeability and porosity of the salt are controlled by the distribution and evolution of damage, so characterization of damage is critical. Lastly, some of the tests are specific to the effect that heat has on the EDZ and the production of brine.

2.5.1 BATS 3 Categorization

The experiments and method development proposed here can mostly be grouped into four primary themes:

- Damage (EDZ) evolution
    - 2.3.3 Mine-by characterization
    - 2.3.5 Fracture network extraction
    - 2.4.1 Brine pressure/permeability method development
    - 2.4.2 Rock stress method development
    - 2.4.3 Gas permeability method development
    - 2.4.5 Sonic velocity method development
- Brine characteristics
    - 2.3.6 Long-term brine inflow sampling
    - 2.3.8 Brine inflow time lapse
    - 2.3.10 ERT with brine injection
    - 2.4.4 In-drift and in situ chemistry monitoring method development
- Heat effects
    - 2.3.1 Long-term heated test
    - 2.3.2 Long-term heated sealed test
    - 2.3.9 DPC effects on EDZ
- Engineered Barrier Systems (EBS) interactions with salt and brine
    - 2.3.4 Historic test re-entry
    - 2.3.7 Seal installation and testing

The large sample collection method development would primarily lead to laboratory experiments, so it doesn't fit into one of these categories directly. Also, some of the experiments or method development apply to multiple categories (e.g., ERT with brine injection applies to both brine and EDZ characterization).

2.5.2 BATS 3 Prioritization

There are several things to consider in prioritizing the experiments and method development. First, how important a topic or its science questions are to the overall mission, and second, how difficult, risky, or costly it is. Lastly, the diversity of ideas or topics should be considered, so that all the effort is not focused on a single category, at the expense of all others.

Table 4. BATS 3 Prioritization.

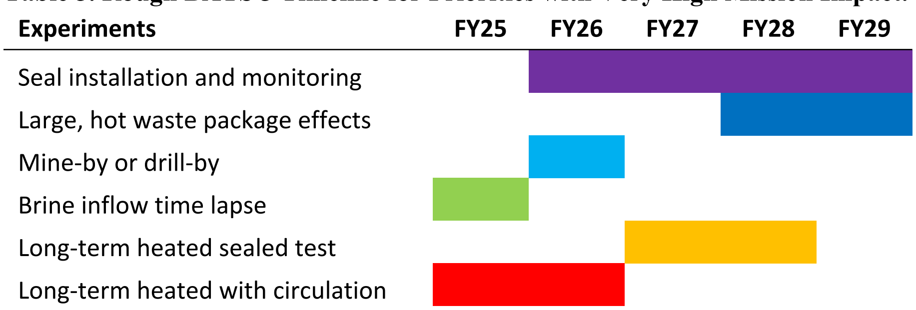
Experiments	Mission Impact	Difficulty/Cost
2.3.1 Long-term heated test	Very High	Medium
2.3.2 Long-term heated sealed test	Very High	Medium
2.3.3 Mine-by or drill-by test	Very High	Medium
2.3.4 Historic experimental area re-entry	High	Low
2.3.5 Fracture network extraction test	Medium	Low
2.3.6 Long-term brine inflow sampling test	Medium	Low
2.3.7 Seal installation and monitoring test	Very High	Low
2.3.8 Brine inflow time lapse test	Very high	Low
2.3.9 Large, hot waste package effects on EDZ test	Very High	Medium
2.3.10 ERT with brine injection test	Medium	Low
Method Developments		
2.4.1 Brine pressure/permeability	Low	High
2.4.2 Rock stress	High	Low
2.4.3 Gas permeability	High	Low
2.4.4 In-drift and in situ chemistry monitoring	Medium	Medium
2.4.5 Sonic velocity	High	Low

In Table 4, the very high mission impact and alignment items (colored in dark green) are the highest priority, regardless of their difficulty or cost. The high mission impact items (lighter green) are a secondary priority if they are low difficulty or cost. The medium or lower impact items are orange if they are a low difficulty or cost and are red if they are medium or higher difficulty or cost.

Experiments and methods may also have different aspects and effects not captured in this simplistic ranking system that contribute to them being more or less important priorities, but Table 4 gives a high-level prioritization of the efforts presented in this high-level test plan.

Items that fall lower down on the priority list may still be worthwhile to conduct (and may fit into the schedule depending on changing priorities), but do not make good candidates for the first round of efforts associated with BATS 3 (Table 5), based on current priorities.

Table 5. Rough BATS 3 Timeline for Priorities with Very High Mission Impact.



2.6 Beyond BATS 3

The BATS 3 testing will allow more focused investigation of key pairs or individual processes illuminated in BATS 1 and 2. The testing capabilities and data collected as part of BATS 3 testing would ultimately benefit eventual follow-on testing at a larger scale (Stauffer et al., 2015), possibly including larger drift-scale demonstrations, similar to those that were previously planned by DOE-CBFO (who owns the WIPP site) as part of the Salt Disposal Investigations (CBFO, 2011) and Salt Defense Disposal Investigations (CBFO, 2013) programs.

Drift-scale demonstrations could include drift-scale cementitious seal emplacement and monitoring, and emplacement of a large, hot waste package with monitoring. Both these drift-scale demonstrations build on very-high priority smaller-scale tests proposed as part of BATS 3.

3.0 MANAGEMENT STRUCTURE

The BATS heater test project is relatively small in scope and, therefore, has a somewhat informal management structure. It is managed as part of the DOE-NE Spent Fuel and Waste Science and Technology (SFWST) Program. Sandia National Laboratories (SNL) serves as the project management lead, while the WIPP Test Coordination Office (TCO) at Los Alamos National Laboratory (LANL) Carlsbad serves as the underground testing coordinator and liaison to the CBFO Chief Scientist and the WIPP site. CBFO owns the WIPP site. SNL, LANL, and Lawrence Berkeley National Laboratory (LBNL) are all contributing to test design, fabrication, and implementation. Site preparation work (e.g., drilling boreholes and ground control) will be conducted by the WIPP management and operations (M&O) contractor Salado Isolation Mining Company (SIMCO). Additional groups are collaborating with the core team, but since their primary funding is external to the project they are not listed explicitly with roles and responsibilities.

The following Roles and Responsibilities are excerpted from SNL et al., (2020) and reiterate those stated in Kuhlman et al. (2021), focusing on the field implementation portions of the project. That reference also discusses roles related to numerical modeling, laboratory analyses, and international collaborations.

3.1 Roles and Responsibilities

Sandia National Laboratories (SNL) Project Manager

- Responsible and accountable to US Department of Energy Office of Nuclear energy (DOE-NE) for executing the Project within scope, cost, and schedule in a safe and responsible manner.
- Provides access to SNL resources, systems, and capabilities required to execute the Project.
- Identifies and manages Project risks.
- Designs and builds components of Project related to gas composition analyses, borehole closure, acoustic emissions, ultrasonic wave velocity, brine sampling, engineered barrier system (EBS) seal components, heaters and packers.
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground.
- Work within the controls established by the test plans and work authorization documentation to implement and operate the testing programs.
- Provides personnel for underground installation, maintenance, and troubleshooting of experimental equipment.

Los Alamos National Laboratory Carlsbad Office (LANL-CO) WIPP Underground Test Coordination Office (TCO)

- Provides interface role between the Project and US Department of Energy Office of Environmental Management (DOE-EM) Carlsbad Field Office (CBFO) and WIPP M&O contractor (Salado Isolation Mining Company, SIMCO).

- Coordinate with DOE-CBFO Chief Scientist during the planning and implementation the Project.
- Provides implementation, maintenance, and troubleshooting technical guidance to Project.
- Designs and builds temperature sensing, data acquisition, and on-site control aspects of Project.
- Provides access to TCO and WIPP resources, systems and capabilities required to execute the Project.
- Provides the mechanism to deliver project funds to the WIPP M&O contractor (e.g., for drilling new boreholes).
- Collects and distributes data from the automated Data Acquisition Systems (DAS) as coordinated with the national laboratory project staff.
- Provides on-site sample collection and sample control processes and resources as requested by the national laboratories project staff.
- Develop (with the national laboratories) appropriate work authorization and work control documentation for testing activities (for SIMCO review/acceptance), compliant with national laboratory and SIMCO requirements, to ensure the safe and consistent conduct of physical scientific work activities in the WIPP underground.

Los Alamos National Laboratory (LANL)

- Provides access to LANL resources, systems, and capabilities required to execute the Project.
- Designs and builds components of Project related to stable isotope analyses.
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground.
- Work within the controls established by the test plans and work authorization documentation to implement and operate the testing programs.
- Provides personnel for underground installation, maintenance, and troubleshooting of experimental equipment.

Lawrence Berkeley National Laboratory (LBNL)

- Provides access to LBNL resources, systems, and capabilities required to execute the Project;
- Design and build geophysical monitoring, including electrical resistivity tomography (ERT) and fiber-optic distributed temperature and strain components of the Project.
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground.
- Work within the controls established by the test plans and work authorization documentation to implement and operate the ERT systems.
- Provides personnel for underground installation, maintenance, and troubleshooting of experimental equipment.

Salado Isolation Mining Company (SIMCO) site M&O Contractor

- Provides labor for constructing Project boreholes.
- Maintains required underground infrastructure for Project including appropriate ventilation, ground control, lighting, communications, and electrical distribution.
- Provides auxiliary services required to conduct the Project including underground access, hoisting, training, environmental, and safety.

3.2 Team Interfaces and Safety

It is mandatory that all WIPP underground science program participants and personnel performing work associated with the science and testing activities in the WIPP underground and on the WIPP site abide by the SIMCO guidelines and requirements referenced in the Integrated Project Team (IPT) Charter for Science and Testing Activities in the WIPP Underground (CBFO, 2016). Scientists and personnel associated with the underground test programs are not only responsible for their own health and safety but are also responsible for the safety of fellow employees, and for the safe operation of the experiment, not precluding TCO and SIMCO oversight of the scientific work. The CBFO holds SIMCO accountable for safe operations at the WIPP and gives SIMCO authority to enforce safety rules and policies on all WIPP science participant organizations.

Work within the WIPP facility is strictly controlled to ensure safety and quality. This is accomplished primarily through an integrated work control and authorization process. All scientific testing activities conducted in the WIPP underground will be conducted under a work control package created in accordance with the process described in the IPT Charter (CBFO, 2016). The process ensures that planned science work scope is appropriately reviewed, authorized, scheduled, released for work, and integrated with the underground controller and field work supervisor for access and support in the underground.

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