Sandia National Laboratories
Los Alamos National Laboratory
Lawrence Berkeley National Laboratory

Department of Energy Office of Nuclear Energy
Spent Fuel and Waste Disposition (SFWD) Program

Test/Activity Plan

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

Spent Fuel and Waste Science &
Technology (SFWST) Milestone: M3SF-21SN010303055

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March 2021

SAND2021-3497 R

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ABBREVIATIONS AND ACRONYMS

CBFO	Carlsbad Field Office (DOE-EM Field Office running WIPP)
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
EDZ	Excavation Damaged Zone
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
M&O	Management and operations (NWP at WIPP)
NWP	Nuclear Waste Partnership (WIPP M&O contractor)
R&D	Research and development
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 behavior
URL	Underground Research Laboratory
WIPP	Waste Isolation Pilot Plant (DOE-EM facility managed by CBFO)

1.0 BACKGROUND AND INTRODUCTION

This document is a high-level test plan for small-scale experimental activities in boreholes in salt at WIPP.

The DOE Office of Nuclear Energy (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 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 a series of Brine Availability Test in Salt (BATS) field experiments conducted underground at the Waste Isolation Pilot Plant (WIPP), a DOE Office of Environmental Management (DOE-EM) Carlsbad Field Office (CBFO) facility for disposal of transuranic defense waste. DOE-NE is working 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 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 particular 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). Investigating brine availability requires characterizing the amount and types of brine present in the salt and the 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 (aside from fractured non-salt interbeds) exist in the Excavation Damaged Zone (EDZ), which is a halo of salt with altered properties surrounding every room or borehole in the underground. We present this plan for future investigations in salt in the following sections (see Figure 1 for locations). The series of borehole-scale BATS experiments are part of a larger plan to conduct field experiments to answer specific technical questions and improve the technical basis for disposal of heat-generating radioactive waste in salt (Stauffer et al., 2015; SNL et al., 2020).

2.0 PURPOSE AND SCOPE

This test plan describes the planned 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, i.e., its thermal-hydrological-mechanical-chemical (THMC) evolution. The high-level technical objectives of the test plan are as follows:

- Measure the thermal-mechanical response of the salt from heating (i.e., temperature distribution and borehole closure);
- Quantify brine inflow from the salt to boreholes (i.e., thermal-hydrological), measuring gas and water composition to better understand source of water (e.g., fluid inclusions, water from clay, hydrous minerals);
- Use modern geophysical methods (e.g., electrical resistivity tomography, fiber optic distributed temperature and strain sensing, acoustic emissions) to characterize the evolution of the salt and brine during heating, cooling, and application of gas pressure in packer-isolated intervals;
- 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, X-ray computed tomography for fractures and rock microstructure);
- Observe the interactions between seal materials (e.g., salt concrete or Sorel cement), host rock (i.e., halite, clay, gypsum, and polyhalite), and brine under both heated and unheated conditions.

While working to understand these technical objectives of the BATS tests, the overarching goal of the SFWST campaign in salt is to gather data to refine our understanding of salt's feasibility as a disposal medium for heat-generating waste. We seek to better understand the EDZ and the distribution of brine in the EDZ, which is an important initial condition to long-term repository performance assement.

2.1 Major Activities: Previous Work

2.1.1 BATS Shakedown Test (1s)

The first phase of BATS (phase 1s, for "shakedown") located in E140 (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 Test in New Boreholes (1a)

The next phase of BATS (phase 1a) was conducted in two arrays with 14 horizontal boreholes each, drilled in N940 (Kuhlman et al., 2020; Figure 1). One array was heated, and a second similarly instrumented control array was left unheated. The boreholes were drilled in Map Units 1 to 4 (see WIPP stratigraphy in Section 2 of Roberts et al., 1999) from February to April 2019. After assembling the required infrastructure and instrumenting the boreholes, the first phase of heating in the BATS 1a heated array occurred during January to March 2020.

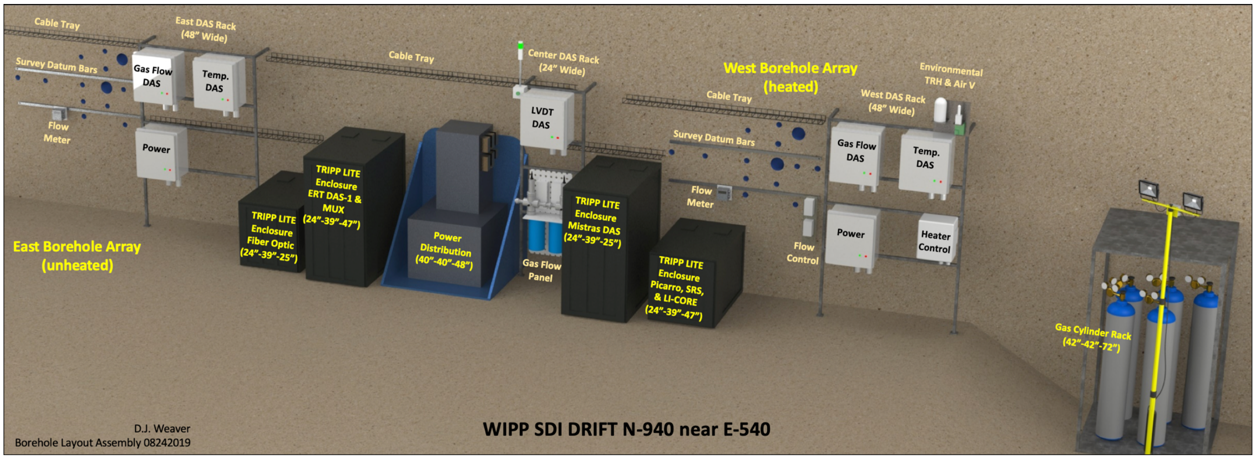

Figure 1. Illustration of BATS 1a drift layout

The main scientific question that motivated the BATS 1a 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 secondly, 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 (~1 to 2 % by volume) is found in fluid inclusions, disseminated clay, and hydrous minerals (e.g., gypsum, polyhalite). Each of these water types and their potential flowpaths 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.

BATS 1a circulated dry nitrogen gas continuously through the heated region (750 W heater, ~120 °C borehole wall temperature 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 high frequency (observations at least every 5 minutes) 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 type K 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 (laboratory measurements are being made to measure salt and brine electrical conductivity with temperature). Acoustic emissions were monitored during heating and cooling, with ~75% of all emissions observed coming from thermal contraction associated with the cool-down phase. Boreholes and cement seals were instrumented to observe relative humidity, strain, and closure. The data acquired during BATS 1a has shed light on several aspects of brine availability and the test has also revealed several aspects of test design that could be improved to refine our understanding.

2.2 Major Activities: Next BATS Phases

2.2.1 BATS 1b & 1c Tracer Testing

Using the heated and unheated array boreholes from BATS 1a, the current phases (as of March 2021) involve additional rounds of heating and cooling with gas (1b) and liquid (1c) tracer tests conducted between packer-isolated boreholes (sources added to packer-isolated intervals in the D borehole, breakthrough monitored via continuous monitoring of the heater and packer (HP) borehole and samples collected from the sampling (SM) boreholes – see Figure 2). 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. Additional information on acoustic emissions and electrical resistivity will also be collected. Brine production into the HP borehole appears to be strongly influenced by pressurization of gas in the tracer source (D) borehole, as part of permeability tests or preparations for tracer tests.

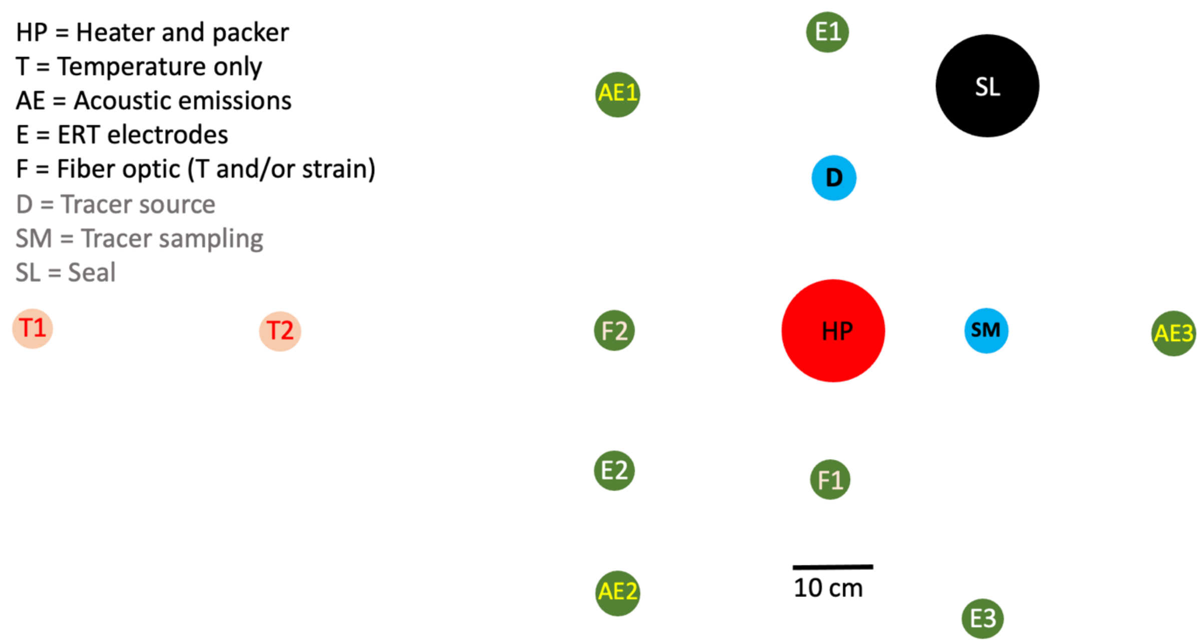

Figure 2. Drift-view layout of boreholes in BATS 1a

Gas tracer tests in the unheated and heated arrays (BATS 1b) began in January 2021, while the heated gas tracer test and the liquid tracer tests (BATS 1c) are planned to follow soon after (planned to start in April 2021).

BATS 1d Cyclical Heating and Cooling

A sequence of repetitive heating and cooling cycles will be conducted in the BATS 1a heated array. The heater controller will cycle on/off or high/low power for relatively short periods of time (e.g., ~1 day on/ ~1 day off), to investigate the repeatability and hysteretic/irreversible behavior of the thermal-hydrological-mechanical response of the salt. The period of the heating and cooling cycle will be based on the characteristic times associated with the processes of interest in salt (Cosenza & Ghoreychi, 1993; Kuhlman, 2019). This will be the last major test planned in the heated array before destructive post-test sampling, targeting summer 2021.

2.2.2 Destructive Post-Test BATS 1a-1d Sampling

Before coring, the HP heater/packer assembly, the heated D packer, the heated seal (SL) mechanical packer, and the heated SM mechanical packers will be removed. The boreholes will be video inspected and scraped/sampled for precipitated salts. The HP borehole will then be stabilized with marked grout or epoxy (e.g., rhodamine dye), to improve the likelihood of recovering intact post-test cores of the region between the HP, D and SM boreholes. The dye would also help to stabilize and mark the pre-existing fractures, to better distinguish them from fractures due to coring, and possibly help preserve the salt/grout interfaces in the SL borehole.

As part of the mobilization of drilling equipment and personnel to drill new boreholes for BATS 2 (October 2021), a series of large-diameter (~12 inch) cores will first be collected in and around the BATS 1a-1d heated array (the unheated array will remain for additional passive monitoring). These cores will be compared to pre-test cores collected in 2019 from HP and SL boreholes, to provide laboratory samples. These samples will be used 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 condition of grout and instrumentation (e.g., ERT sensors and thermocouples, by overcoring one or more of the grouted E1-E3, F1-F2 or T1-T2 boreholes);
- 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).

Post-test over-coring should utilize the DIAMEC 232 coring rig purchased by DOE-NE in 2019, to allow underground M&O and TCO personnel to gain experience using it before drilling the new BATS 2 boreholes.

2.2.3 BATS 2 New Heated Array

To better characterize the brine released from the salt immediately after drilling, the follow-on heated BATS 2 array will be coordinated to be drilled, instrumented, and have heated testing begin in a shorter time frame than was possible in BATS 1a. Brine inflow rate decays rapidly from an initial peak after drilling, requiring a coordinated effort to observe early time behavior. The drilling of the BATS 2 array is targeted for October 2021 and will occur after destructive post-test sampling of the BATS 1a-1d heated array, locating the new heated array immediately west down the N940 drift, near where the gas bottle storage rack is now (see Figure 1).

The new BATS 2 heated array will be similar to the BATS 1a-1d heated array with the following modifications:

- The time between drilling and turning on the heater will be significantly reduced:

  - Long-lead equipment (e.g., inflatable packers, heaters, thermocouples) will be procured and delivered before drilling begins, to allow integration and testing before installation;
  - Packers, heater, and other in-borehole equipment will be ready for integration and installation at the beginning of drilling, to eliminate wait time after drilling;
  - Liquids will be sampled from open boreholes twice a week, starting immediately after drilling (using modified sampling equipment assembled for BATS 1a);
  - Boreholes will be surveyed and video logged as soon as possible;
  - Grout recipes may be modified to reduce viscosity and water content simultaneously (grout recipe should not use "expansive" cements);
  - Grouted sensors (thermocouples, fiber optics, and electrical resistivity tomography electrodes) will be installed as soon as possible; and
  - Laboratory-made seals will be created with enough lead time to allow proper curing before installation.
- The new heated array will be centered at a lower elevation, completed mostly in the argillaceous Map Unit 0 (MU-0), rather than on the clean halite of Map Unit 3 (MU-3), where the BATS 1a-1d array was centered.
- The acoustic emissions (AE) and electrical resistivity tomography (ERT) boreholes will be located further radially from the central borehole, possibly splitting the same number of sensors between 4 instead of 3 boreholes.
- Most boreholes will be made 1 to 2 feet longer than in the BATS 1a-1d boreholes, to locate more of the instrumentation deeper into the salt, further from the access drift EDZ.
- Boreholes with grouted instruments will be drilled at 2.1-in diameter, rather than 1.75-in diameter, to reduce the volume of areas where grout cannot adequately penetrate (a compressed-air driven– rather than hand-cranked – grout pump will also be used).
- Coring will be done with new thin-kerf coring bits, which may help produce longer sections of intact core.
- Non-expansive grout will be used. We will consider adding a small-diameter (~1/8-in) plastic drain tube with the grout and sensors to reduce brine pressure from the grout curing process. Ensure any drains do not become leakage pathways.
- We will possibly utilize a higher-power (>750 W) and possibly longer (>69 cm) heater to drive the system.

2.2.4 BATS 3 Flexible Borehole Cluster Investigations

BATS phase 3 will be planned in more detail after the start of BATS 2. It will involve several smaller tests seeking to isolate coupled THMC process effects observed in BATS 1a-1d and BATS 2 tests, using a strategy of parallel testing in smaller groups of boreholes, rather than a coordinated test with multiple simultaneous processes and observations. Brine availability (i.e., distribution of brine and the evolution of the EDZ) is still a primary 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 we are monitoring in salt are coupled, and difficult to separate 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 (N940 near E540 is the current BATS 1a 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.

2.2.5 New BATS Infrastructure

Based on experience gained from the shakedown test (Boukhalfa et al., 2018; 2019; Guiltinan et al. 2020) and BATS 1a/1b/1c/1d in the built-for-purpose boreholes in N940 near E540 (Kuhlman et al., 2020), building up additional typical infrastructure found in international underground research labs (URL) 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. Significant benefit could be derived from improved environmental enclosure for personnel, computers, and certain sensitive 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. To allow more flexible testing over longer time periods, BATS would benefit from a conditioned, reliable, monitored mine power distribution system and local battery backup (i.e., uninterruptable power supply) located within an environmental enclosure.
4. For BATS, network (i.e., data and phone) access from an environmental enclosure to the surface would allow remote monitoring and contact with the experiments during possible reduced underground access.
5. Well-lit, lockable workspace in the environmental enclosure 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 in underground (e.g., ~2-in and ~5-in capped steel pipes), since they often must be disassembled to get them into the WIPP underground.
6. Accurate borehole surveying/logging tools (survey and logging tools may also be rented or sub-contracted)

Some of this infrastructure would 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.

Any of this infrastructure could be utilized as soon as it is added in ongoing phases of BATS, but the primary goal would be for it to be ready for BATS 3 investigations, since the space in the N940 drift around BATS 1a-1d and 2 is limited.

2.3 Major Activities: Coring, Drilling and Sample Collection

2.3.1 BATS 1a-1d boreholes

The heated and unheated arrays of horizontal boreholes for BATS 1a were drilled Feb to Apr 2019 and are located on the south wall of N940 west of the E540 intersection in the SDI area. The horizontal boreholes are 1.75, 2.1, and 4.8 inches in diameter. Only the 4.8-in diameter boreholes were cored; the rest were drilled with no core recovery. The as-built description of the BATS 1a array is given in detail in Kuhlman et al. (2020); the layout of the heated array boreholes is shown in Figure 3. The unheated array is similar in design, located approximately 20 ft east of the heated array, closer to the E540 intersection.

At the end of the cyclical heating and cooling tests in summer 2021, the heated BATS 1a-1d array will be destructively sampled (the unheated array will continue to be passively monitored). This over-coring campaign will be coordinated with the mobilization for drilling the new BATS 2 boreholes. Some of the boreholes may be stabilized with marked grout or epoxy (e.g., fluorescent dye) before overcoring, to increase the likelihood of intact core recovery. Large (~12-in diameter) core will be collected in the region around where liquid tracers were added (D, SM, and HP boreholes). The overcoring will sample salt near the heater in the HP borehole that had been subjected to at least three rounds of heating and cooling, for comparison against pre-test samples. The comparison of pre- and post-test cores will help quantify the amount and types of brine available in the salt, and how this brine has been affected by heating. At least one grouted instrument borehole will be overcored to inspect the grout and condition of sensor wires, to allow possible improvement and iteration of the design.

2.3.2 BATS 2 boreholes

The new BATS 2 heated array be laid out in a similar pattern to the heated array in BATS 1a but centered lower in the argillaceous MU-0 horizon (BATS 1a is centered on the clean halite MU-3 horizon). In the BATS 2 array, the acoustic emission (AE) and electrical resistivity tomography (ERT) boreholes will be moved out radially from the central HP borehole. Except for the AE boreholes, the boreholes will also be made 1 to 2 feet longer than in BATS 1a, to move the testing interval further away from the EDZ of the access drift.

The smallest-diameter boreholes from the BATS 1a array (1.75 inch) that will have instrumentation grouted into them (E1-E3, F1 & F2, T1 & T2) will be drilled larger diameter ≥2.1-in diameter, to allow easier circulation of grout without adding additional water to the grout mixture. The HP and SL boreholes will be cored, with core collection and logging similar to the BATS 1a boreholes.

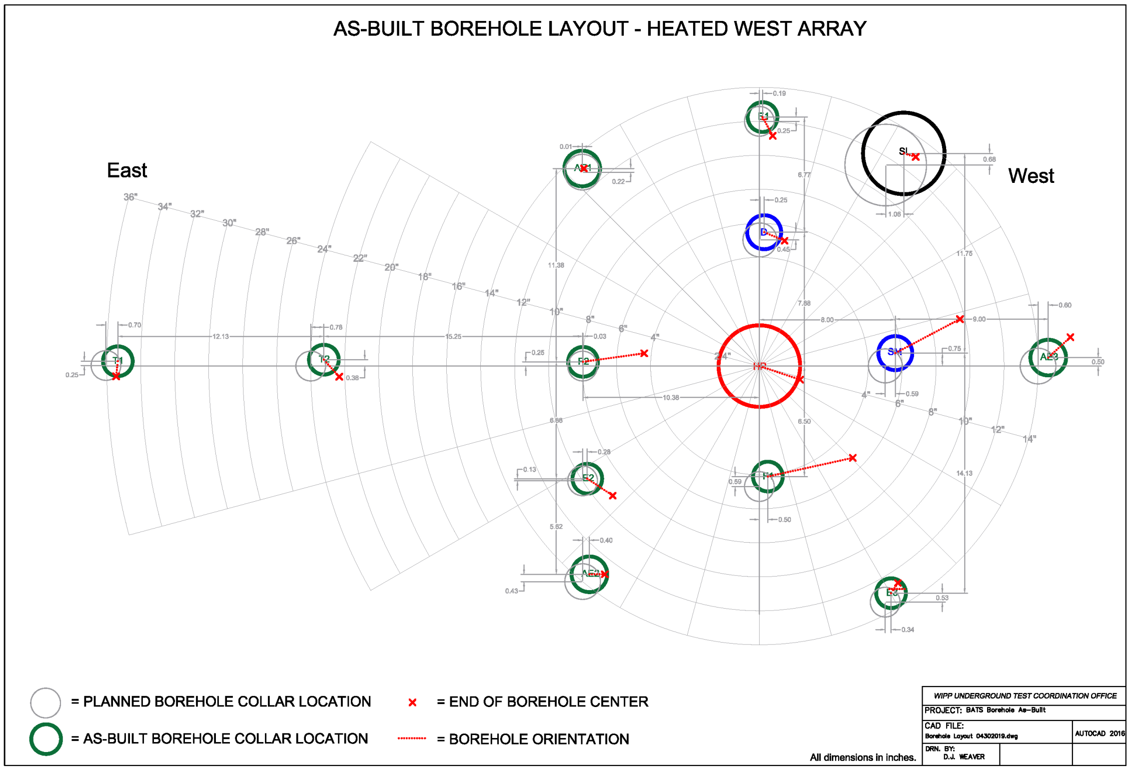

Figure 3. Heated array boreholes as built for BATS 1a (Kuhlman et al, 2020)

2.4 Major Activities: Testing Objectives

2.4.1 BATS 1b/1c

For BATS 1b/1c, the existing arrangement of boreholes and instrumentation used in BATS 1a will be used to execute gas and liquid tracer tests in each array. The gas tracer test will be conducted first (BATS 1b), and the more invasive liquid tracer test will be conducted afterwards (BATS 1c). The gas tracer is a mixture of 5% each SF_6, Ne, and Kr in a N_2 carrier gas. The liquid tracers are isotopically distinct water from a high-elevation snow source, with perrhenate and blue, fluorescent dye (Na-naphthionate) tracers. The tracers will be added to the D boreholes behind an inflatable packer, and samples will be collected from the HP (gas) and SM (liquid) boreholes. The spatial distribution of liquid tracers after the test will be estimated from small sub-samples taken from 12-in diameter cores collected during destructive post-test coring.

2.4.2 BATS 1d

For BATS 1d, the heater will be operated cyclically for several cycles over relatively short time periods (i.e., ~1 day heating, ~1 day cooling for 1 to 2 weeks) to investigate the repeatability and overall changes in the thermal-hydrological-chemical-mechanical response of the salt subjected to multiple heating/cooling cycles. Some aspects of brine availability have been fairly repeatable (e.g., thermal response), while other aspects are not (e.g., brine production). This cyclic part of the test will investigate these non-linear history effects and any possible frequency-dependence of the response more fully, to aid with future test design and model process validation.

2.4.3 BATS 2

Once the new BATS 2 boreholes are drilled, the grouted-in sensors (fiber optic distributed strain and temperature sensing, thermocouples, ERT) will be installed as soon as possible, to allow time for any sensor transients during grout curing to pass before the test begins. Acoustic emissions sensors will be moved from the BATS 1a heated array. Packers (both mechanical and inflatable) will be available and installed into boreholes as soon as possible after drilling.

The heater/packer assembly for the HP borehole will be in the WIPP underground ready to be installed by the time drilling is complete. The laboratory-constructed cement seal for the SL borehole will also be built, cured, and in the WIPP underground ready for installation before the end of drilling.

Once the monitoring equipment is installed in the boreholes, the in-drift support infrastructure (computers, dataloggers, and instrumentation) will be moved back into place, after much of it was moved to make room for post-test coring operations after the end of BATS 1d. The plumbing of the ¼-inch gas circulation tubing will go from UHP N_2 tank, to the HP borehole, then to the gas analyzers. Gas tubing exiting the heated array will be insulated ¼-inch stainless steel tubing. Background flow of dry N_2 will begin as soon as possible to gather background data and prepare the HP borehole for turning on the heater.

The heated experiment will include at least two 8-week heating/cooling cycles (~4 weeks heating, ~4 weeks recovery) to characterize the liquids and gases given off by the salt. The gas permeability of the salt will be measured in a nearby borehole (i.e., D) before, during and after heating to quantify the effects of thermal expansion and stress redistribution on the porosity and permeability of the salt in the excavation disturbed zone.

After these first two longer heating/cooling cycles, another series of tracer tests will be conducted in the heated array, similar to the tests conducted in MU-3 as part of the BATS 1b/1c.

2.4.4 BATS 3

Several focused experiments, including further investigation into aspects already tested as part of BATS 1a-2 test, will be done in BATS 3. 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. The details of the BATS 3 experiments will be planned after the BATS 1b-d, and 2 experiments, but the general ideas of proposed experiments and measurement methods are listed in the following paragraphs.

Sealed Heated Borehole Experiment

This proposal involves heating a borehole for several weeks (similar to BATS 1a and 2), but without N_2 circulation during the test; only removing gas and liquid after the completion of cooling. A sealed test interval would be more like the conditions expected in an actual radioactive waste repository than one with forced circulation of dry gas, but the brine production data are only observed at the end. Any observations during the heating would have to come from satellite boreholes or be measurements inside the sealed borehole without circulating N_2. The total amount of water produced, and the amount and types of minerals precipitated would be compared to the results of BATS 1a-c and BATS 2, where the water vapor was constantly removed during the test (i.e., different borehole boundary conditions). ERT and AE may be used to monitor this test to see what impact moisture in the borehole has on the system response. In the 4-borehole brine migration test conducted at Asse in the 1980s, two of the boreholes were sealed, while two of the boreholes had gas circulated through them (Rothfuchs et al. 1988). In the Asse test brine production amounts were lower in sealed boreholes compared to unsealed boreholes.

Long-term Heated Borehole

This proposal involves heating a borehole while removing inflowing brine with circulating N_2 (similar to BATS 1a and 2), but for an extended period of time. This test would be used to explore how stable the production brine is over longer periods of time, when the borehole is maintained above the brine boiling point. In a future heat-generating waste repository, we expect the heat associated with waste packages over years to cause dryout and accelerated creep closure around the waste. This type of test may require battery backup to maintain a constant heat source for months to years (i.e., across possible WIPP short-term power disruptions in the underground).

Pressure/Stress Measurements 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). Fluid pressure can be measured in a brine- or oil-filled packer-isolated borehole interval (Roberts et al., 1999; Beauheim & Roberts, 2002), while stress can be measured using grouted-in directional pressure sensors (Stormont et al., 1984; Munson et al., 1997b). These data will be useful for integration of efforts between BATS and possible additional geomechanical investigations going on at WIPP.

AE Measurements During Drilling Experiment

A significant EDZ surrounds the access drifts. A smaller EDZ surrounds each borehole. The EDZ is the primary source of permeability and porosity, which allow brine and gas migration. We propose investigating the rapid development of the EDZ around boreholes. AE monitoring can help reveal the extent and timing of this damage, which is the primary pathway by which brine arrives in the BATS boreholes. This type of monitoring could be conducted while drilling different sizes or combinations of boreholes. Logistically, this type of test may require installing the AE sensors in boreholes completed from an adjacent drift (i.e., around a corner or pillar), to minimize interference between the listening AE 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).

Characterize EDZ Fracture Network Experiment

To better characterize fracture networks in the EDZ, we propose injecting colored epoxy or grout into the near-drift EDZ fracture network, then over-core or mine 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). It is difficult to characterize the fractures in situ, since by definition cores cannot sample large through-going fractures. Preserved fractures will then be observed first non-destructively via X-ray CT scans and then destructively by dissolving away the salt after sampling. If successful, the process could be repeated at different locations around the perimeter of the room (e.g., middle of wall, corners, floor or back). Information about the distribution, orientation, and aperture of fractures would be key for constraining flow models of processes in the EDZ.

Brine Inflow and Sampling Experiment

To better characterize the variation in brine availability due to lithology (i.e., more or less clay, more or less polyhalite), we propose a series of horizontal boreholes at different elevations, each completed in a single map unit. The boreholes will be cored and video logged to better characterize the lithology encountered. They will be sealed and sampled for brine volume and composition at least weekly under ambient conditions for months (building on observations made historically at WIPP by the M&O contractor, e.g., Deal et al., 1995). Brine chemistry is known to vary between map units or marker beds (Kuhlman et al., 2017). Observations of brine production (i.e., quantity of brine through time) and samples for 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.

Gas Permeability Testing and 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).

EBS/Seals Testing with Permeability Experiment

Based on the results of post-test sampling of cement seals from BATS 1a-1d, we will install, monitor and sample different formulations of laboratory- and field-constructed cement plugs along with improved instrumentation. 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. 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.

In-Drift and In-Situ Chemistry Methods

Brine composition and water isotopic makeup are key indicators of brine source, a key component of brine availability (brine from fluid inclusions, clay, or hydrous minerals have different compositions). Previous field testing has observed generation of acidic condensate (Kuhlman et al., 2017; Section A-2.3). 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. We will perform similar sampling and observation of brine, gas, and water composition done during BATS 1 and 2, in combinations with other experiments. We will explore options (e.g., X-ray fluorescence) for in-borehole and in-drift monitoring of fluid chemistry (Kipnis et al., 2020).

Time-Lapse of Efflorescence and Stalactite Accumulation Method

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 precipitate in boreholes and fracture development around excavations could also be insightful. These observations could be done as part of other experiments.

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., 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 humidity or brine facilitates accelerated creep under these circumstances. The impacts of strain at low deviatoric stress may be important to these types of long-term buoyancy model predictions. Observations of these small strains require very controlled conditions to monitor small strains but would be worth investigating if technically possible (Bérest et al., 2019).

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. We will make detailed measurements of borehole closure, room closure, and brine inflow under heated and unheated conditions. We may also combine these measurements with brine pressure and geomechanical stress measurements. 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. It could 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 (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.

Advanced Spatial Characterization with Drones and 3D Laser-scanning

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.

A large number of experiments were conducted in the WIPP underground in the late 1980s into early 1990s (Matalucci, 1987a; 1987b; Munson et al., 1997a). 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).

2.4.5 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 ultimate drift-scale demonstrations as 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.

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 Nuclear Waste Partnership (NWP). 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), 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 DOE 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
- Designs and builds components of the Project related to borehole closure, acoustic emissions, ultrasonic wave velocity, and brine sampling
- Designs and builds components of the Project related to engineered barrier system (EBS) seal components
- Designs and builds components of Project related to heater 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 (Nuclear Waste Partnership, NWP)
- 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 NWP review/acceptance), compliant with national laboratory and NWP 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 (ERT and fiber-optic distributed temperature and strain) monitoring 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

Nuclear Waste Partnership (NWP) 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 NWP 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 NWP oversight of the scientific work. The CBFO holds NWP accountable for safe operations at the WIPP and gives NWP 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.

4.0 ACKNOWLEDGEMENTS

BATS is only possible through continued collaboration and coordination between multiple organizations. The authors of this plan represent the major contributing organizations, but this work is being conducted by a much larger team. The BATS team includes: Kris Kuhlman, Melissa Mills, Rick Jayne, Charles Choens, Courtney Herrick, Yongliang Xiong, Martin Nemer, Ed Matteo, Jason Heath, and Matt Paul from Sandia National Laboratories; Phil Stauffer, Hakim Boukhalfa, Thom Rahn, and Eric Guiltinan from Los Alamos National Laboratory; Shawn Otto, Brain Dozer, Dave Guerin, and Doug Weaver from the WIPP Test Coordination Office; and Yuxin Wu, Jonny Rutqvist, and Mengsu Hu from Lawrence Berkeley National Laboratory.

The BATS team thanks the DOE Office of Nuclear Energy (DOE-NE) Spent Fuel and Waste Science and Technology (SFWST) campaign for continued financial support, and the DOE Carlsbad Field Office (CBFO) for providing support through the Test Coordination Office and the WIPP Management & Operation (M&O) contractor for drilling boreholes and providing electrical power and access.

The authors thank Ernie Hardin and Prasad Nair for reviewing the test plan and providing insightful comments.

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NOTICE:
This report describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

APPENDIX E
NTRD DOCUMENT COVER SHEET[1]

Name/Title of Deliverable/Milestone/Revision No.	Brine Availability Test in Salt (BATS) Extended Plan for Experiments at the Waste Isolation Pilot Plant (WIPP)
Work Package Title and Number	Salt Disposal R&D - SNL
Work Package WBS Number	SF-SN01030305
Responsible Work Package Manager	Kristopher L. Kuhlman. (Name/Signature)

Date Submitted: 04/30/2019

Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-1 ☐ Nuclear Data	☐ QRL-2	☒ QRL-3	☐ QRL-4 Lab QA Program[3]

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

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1 ☐ Other

This Deliverable was subjected to:

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

Name and Signature of Reviewers

Ernie Hardin

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

- *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone.*

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

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