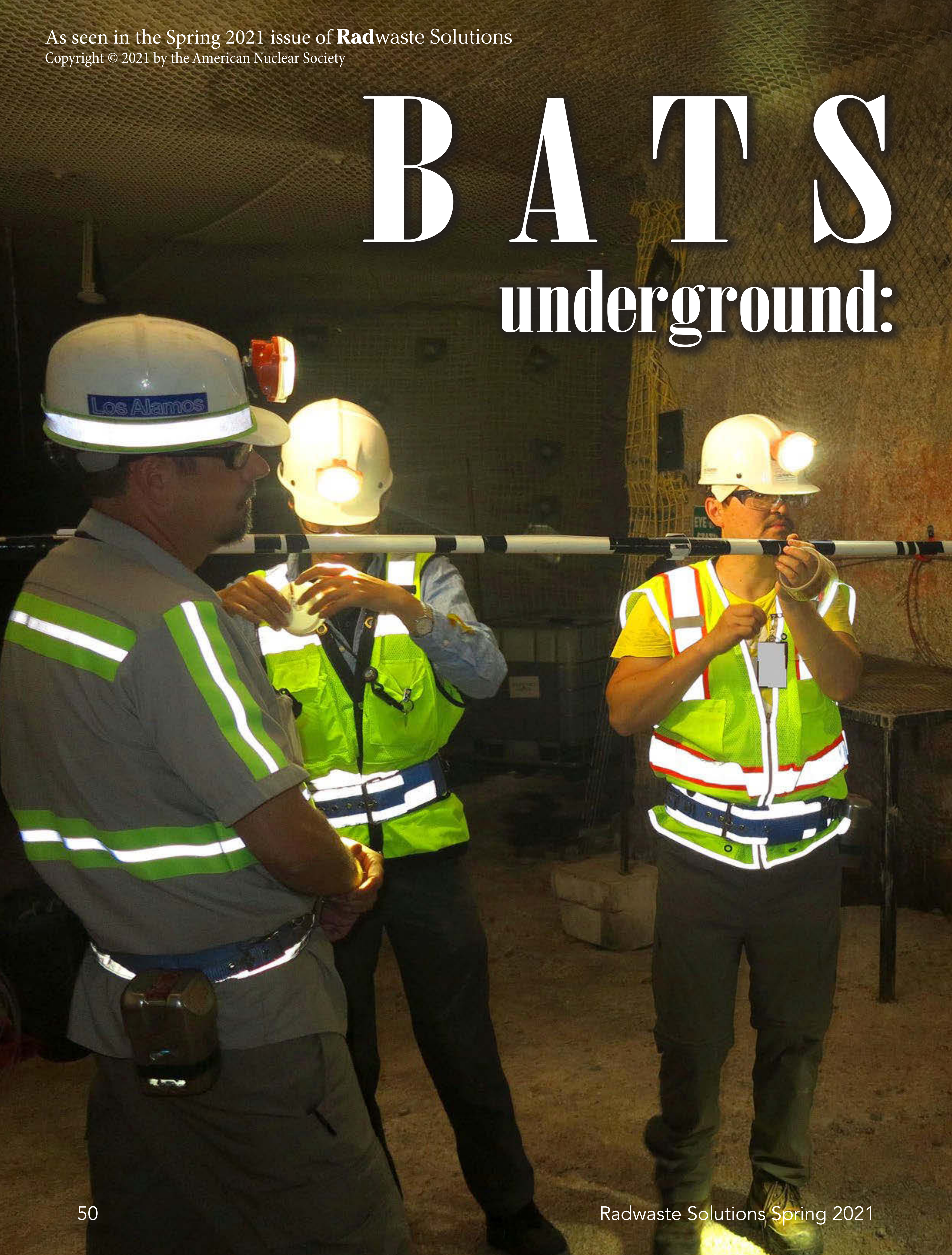


BATS underground:

Brine and the long-term safe disposal of high-level waste in salt

Researchers install test equipment into a borehole in the WIPP underground. Photos courtesy of DOE/LANL.

BY KATHARINE COGGESHALL

Can high-level nuclear waste be safely stored in natural salt formations? The Department of Energy's Office of Nuclear Energy (DOE-NE) aims to answer that question with an unequivocal "Yes." To do so, they enlisted the help of three national laboratories and an existing defense waste repository in New Mexico.

"The Waste Isolation Pilot Plant is the final home of transuranic (waste containing elements above uranium in the periodic table) radioactive waste in natural salt 2,150 feet below the surface," said Phil Stauffer, Los Alamos National Laboratory computational earth scientist. "This is non–heat-generating waste accumulated through Cold War defense activities."

The Waste Isolation Pilot Plant (WIPP) is ideal for permanent disposal because the salt rock effectively seals the radioactive waste from the environment. The salt deposit was created 250 million years ago—before dinosaurs walked the earth—and has remained stable. Therefore, it is highly likely to continue to remain stable for the time it will take the radioactive waste being disposed of there to lose most of its radioactivity and be deemed safe.

"Additionally, the chloride in the salt reduces possible nuclear criticality concerns, and rock salt can actually heal its own fractures," explained Kristopher Kuhlman, Sandia National Laboratories earth scientist, "so when we mine access rooms and hallways to emplace waste, the salt effectively and permanently seals it off from the biosphere."

Given these strong benefits, salt disposal appears to be a top contender for all types of nuclear waste, but there is at least one main difference to consider.

The salt rock geology at WIPP currently seals in radioactive waste generating little heat, but this type of rock could also be well-suited for storing more radioactive waste that generates copious heat. That difference—heat generation—calls for research to support a new type of safety assessment that scientifically supports disposal of higher activity nuclear waste in salt. Heat is a key ingredient in chemical reactions and phase transitions, and higher amounts of heat can liberate the small amount of water associated with the salt (about 1–2 percent of the salt by weight). Heat can mobilize the tiny pockets of water trapped inside and in between the salt crystals as well as the water in clay and hydrous minerals. If any open pathways exist, this salt water, or brine, could carry radionuclides off-site, which could impact the surrounding environment and its inhabitants.

In fact, brine has numerous consequences, both good and bad, including neutron absorption and steel container corrosion. Understanding brine availability—the distribution and movement of brine—especially as it relates to heat-generating waste, is a key factor in understanding how to safely dispose of high-activity waste, such as spent nuclear fuel from commercial reactors and high-level waste from defense activities, in natural salt formations.

Therefore, determining where this small amount of brine currently exists and the behavior of where it is going and flowing as heat enters the equation in the near term will aid in understanding brine distribution over longer time periods.

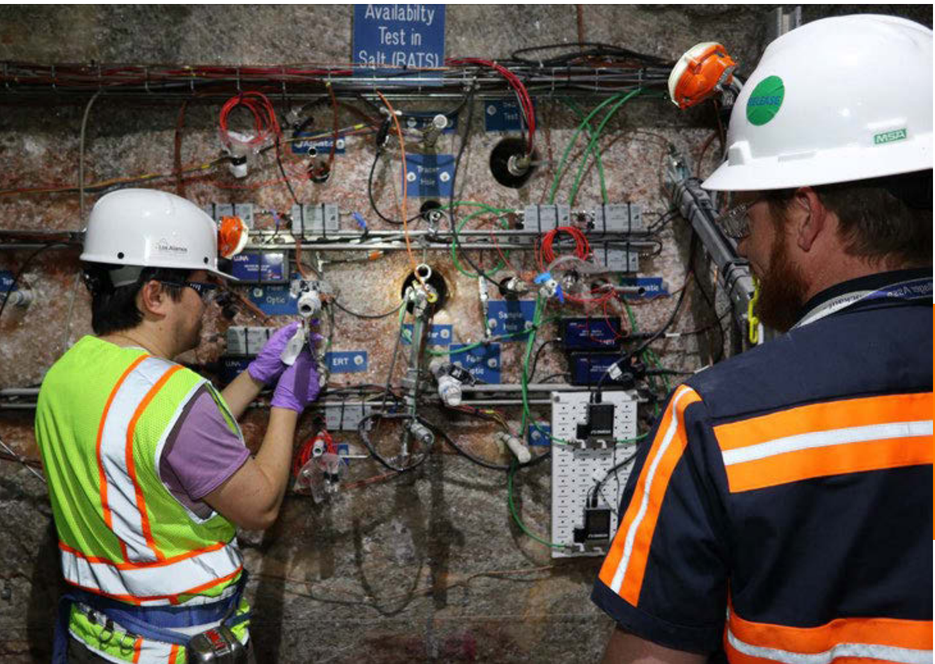
Enter BATS

In 2017, Los Alamos, Sandia, and Lawrence Berkeley national laboratories designed and began implementing the Brine Availability Test in Salt (BATS) project as part of the DOE-NE Spent Fuel and Waste Science and Technology research campaign. The goal of BATS is to better understand and predict brine availability in the damaged area immediately surrounding a salt repository. The damage is created by the very excavation process that creates the rooms used to access the underground. Far away from the excavations, the salt remains undisturbed, whereas near the excavations, damage can change the salt. The damaged salt behaves differently, and BATS is investigating how brine and heat move through and affect the damaged halo surrounding each drift in a salt repository.

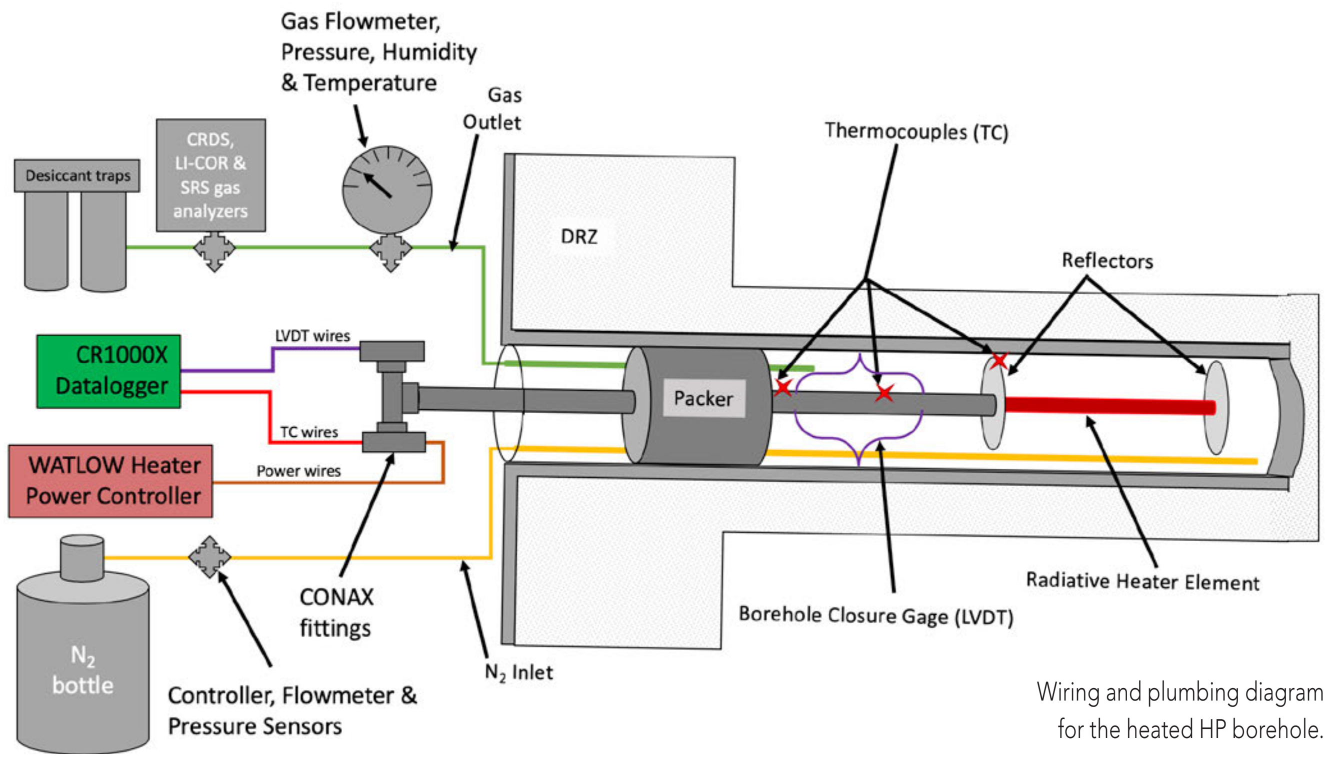
For example, at WIPP, areas for waste storage are mined one at a time, close to when they will be filled with waste. The salt flows (creeps) very slowly, analogous to how tar or honey flow. Typical rooms mined in the underground at WIPP close at about the rate fingernails grow—a few inches per year. This salt creep requires continual maintenance if the mined areas are to remain open.

Additionally, BATS is the first experiment to seek to understand different types of brine. Not all brine is the same, and as a consequence, brine availability differs depending on the water source. The BATS researchers are considering hydrated minerals, water found in clay among the salt, intragranular brine inside salt crystals, and brine between grains as water sources.

"These water sources respond differently to changes in pressure and temperature," Kuhlman said. "So, if you want to know how much brine will flow into an excavation and what timing it has, you need to understand how each of the different types of brine contribute to it."



The first BATS tests were run in existing horizontal boreholes at WIPP, which were previously drilled for other purposes. Horizontal drilling allows for uniform drilling through a salt layer while avoiding non-salt (clay or anhydrite) layers known to exist in rocks above and below.



Wiring and plumbing diagram for the heated HP borehole.

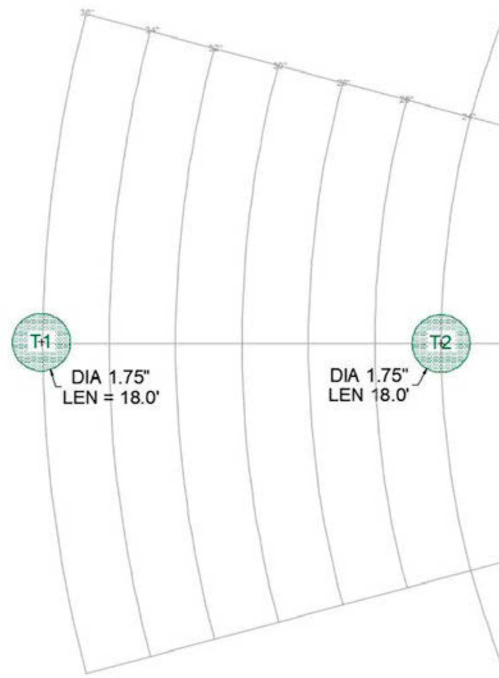
To simulate heat-generating waste in a salt disposal room, the team placed a heater set to 120 °C (250 °F, like a warm oven) inside a small drilled-out hole in the wall. The heater was then surrounded by instruments in other similar boreholes to measure the varied responses of the salt to the additional heat. There are thermal processes (heat moves from hot to cold areas), hydrological processes (water flows downhill), mechanical processes (rooms slowly creep closed and salt expands when heated), and chemical processes (more salt dissolves in hotter water and boiling away the water in the brine precipitates salt). These, and many more complex and coupled processes in the salt, contribute to the observed brine availability.

As Kuhlman explained, “To predict the amount of brine that would flow into a future hot repository for radioactive waste, we first work to understand and predict the amount of brine that would flow into a heated borehole as part of BATS.”

As a control, a similar array of boreholes was left unheated. A complete technical understanding of all the processes expected to happen in the salt provides confidence in the researchers’ ability to predict that the salt will safely and permanently contain the radioactive waste.

There is a great deal of complexity when it comes to predicting and modeling salt systems because the important variables and processes key to controlling the thermal, hydrological, mechanical, and chemical responses are so tightly interconnected. Both the excavation damage and the heat generation impact the balance of the system. Salt is essentially thermally activated; the system changes rapidly in a number of ways—many of which are coupled. For example, high temperatures speed up creep closure, with creep, damage, and healing all changing how the salt responds. BATS is monitoring brine migration to the boreholes, a process very sensitive to these changes in the salt. The salt’s properties change depending on whether the heater is on or off, and this is important to understand because the heat generation from radioactive waste will not be uniform in space for a future repository, as some waste is hotter than other waste, and radioactive decay is such that the heat level changes over time.

The coupling and feedback of processes makes simulation challenging, as it must take into account humidity, water distribution, brine composition, salt permeability, and much more. As one variable changes, the others may change in response, which creates a moving target in terms of calculations. The data that the BATS project is collecting will go a long way toward improving our understanding and predictive models of these processes, which will help us forecast the evolution of the near-drift region.



The shakedown

With so many equipment, safety, and environmental variables to consider, the researchers opted to perform an initial shakedown test, also called BATS Phase 1s, which provided foundational learning for BATS. The shakedown began in June 2018 and ran for nearly a year, until May 2019. It marked the first heated borehole salt experiment conducted underground at WIPP in more than 28 years.

"The lessons learned and insights gained in this initial testing were vital to the design and implementation of the larger-scale experiment," Stauffer said.

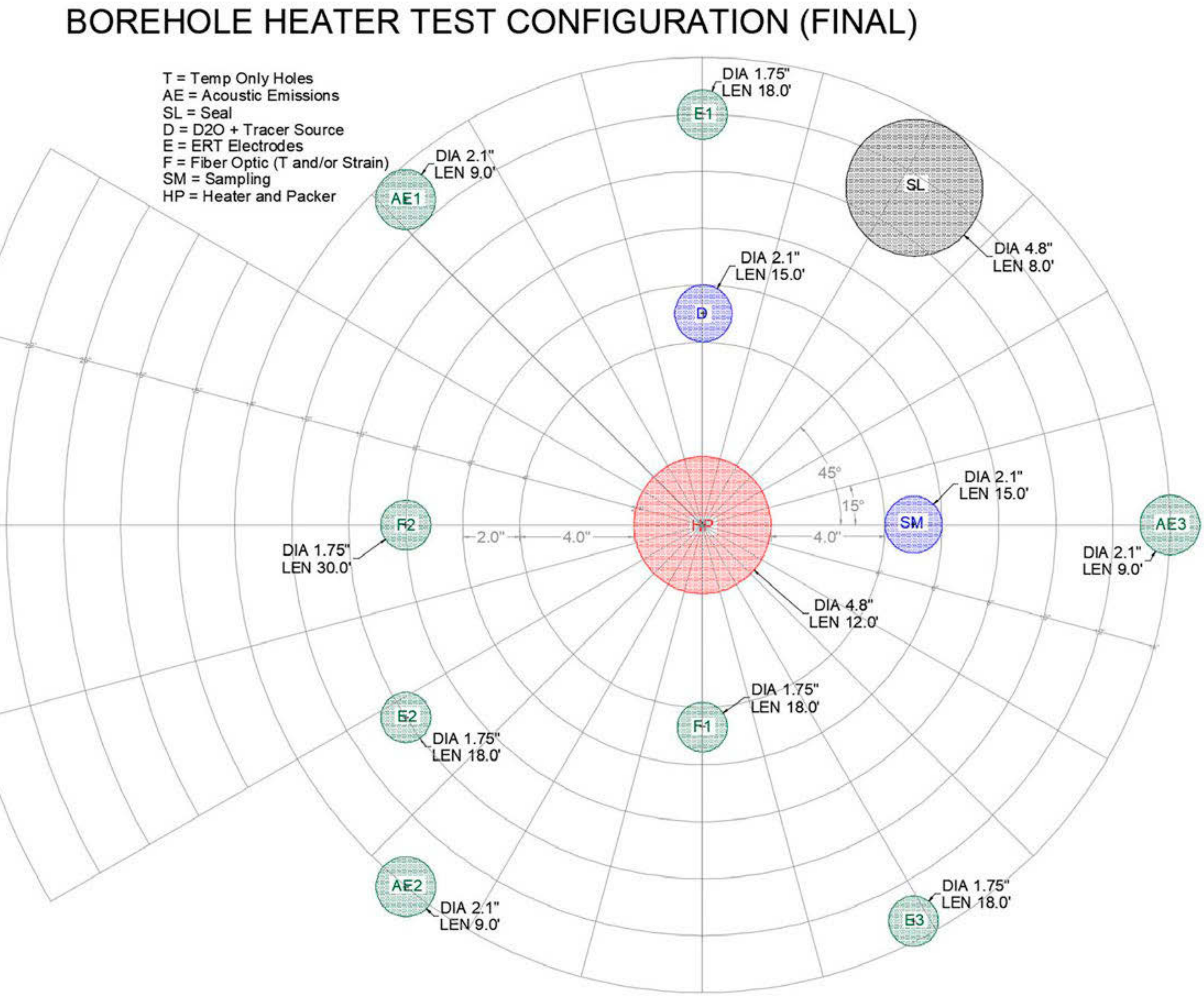
Those foundational lessons included iterating to find an ideal heater design. The original stainless steel block heater the researchers tried did not put enough energy into the system to achieve the targeted 120 °C temperature. Due to the insulating air gap (approximately 1 inch) around the block heater, the temperature at the monitoring boreholes only reached 35 °C. Therefore, the original design was ultimately swapped for a 750-Watt quartz lamp infrared heater, which did in fact deliver the constant temperature desired through radiative energy coupling. The infrared heater was isolated behind an inflatable packer. Dry nitrogen gas flowed through the interval isolated behind the packer, and this gas stream was analyzed for humidity before passing through two desiccant traps, which were weighed to determine the amount of water removed from the borehole. These measurements were compared with those of the gas analyzers.

Establishing the appropriate distribution of liquid pressure and the balance of water and gas (saturation) in the salt around the boreholes are key features needed as part of proper model development.

"There is an iterative loop between the collection of field data and the modeling," Stauffer explained, "and we are always looking for more revealing data sources to help us improve our modeling and understanding."

The shakedown thermal-hydrological model used a 3-D solution mesh containing more than a million nodes, centered upon the central heated borehole. The solution mesh coarsened while moving away from the heater to reduce computational expense where less detail is needed, while keeping artificial boundaries far enough away to reduce their effects on the prediction. The model considered the central borehole as three zones: an air-filled zone, the inflatable packer, and the heater.

This 3-D model was used to predict how the heat and



The borehole layout plan for BATS test array.

brine will equilibrate around the boreholes over a period of years. Additionally, a simpler 2-D radially symmetric model allowed for more rapid investigation of the thermal properties of both the intact salt (far from the boreholes) and damaged salt (near the boreholes). This simpler mesh consisted of only 3,458 nodes and allowed more efficient investigation into processes influencing formation temperature. These and other numerical models will be further constrained (i.e., improved) by data from laboratory measurements of thermal, mechanical, and electrical properties being conducted on salt cores at Sandia National Laboratories.

"We often can't afford to look at all the processes going on in the salt at the same time in the models because it's too complex, so we try to isolate specific processes, which allows for more rapid model-to-data validation," Stauffer said. It is difficult to design an experiment that provides the right data for the modelers, is straightforward for the field team to implement, and will not be overly sensitive to secondary processes or phenomena. While there is always room for improvement, the researchers and the WIPP Test Coordination Office have largely been successful in implementing experiments that provide the needed data.

Working with the Test Coordination Office, the researchers have learned some of the ins and outs of working at WIPP. It can be difficult to bring some equipment underground, sometimes due to physical size constraints (fitting large sections of tubing into the elevator to the underground) and other times due to procedural constraints associated with working at WIPP (an active radioactive waste disposal facility with strict environmental safety and health regulations). Research in the underground at WIPP has taught the BATS team about the effects brine, dark, and salt dust can have while working with sensitive electronics. Guided by the WIPP Test Coordination Office, the BATS team took a cautious and stepwise approach to getting their experiments set up and running in the underground.

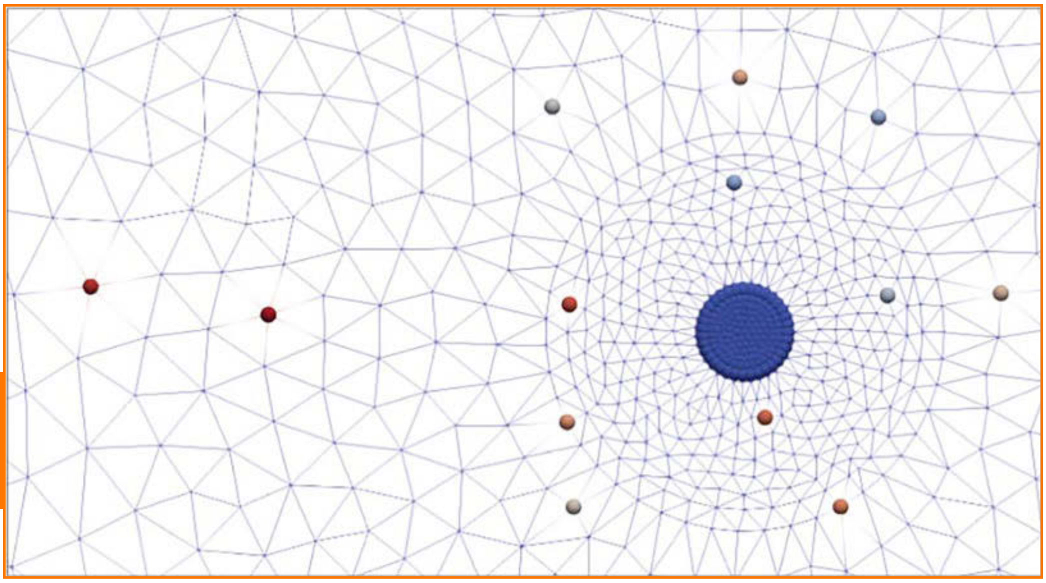
The results of the shakedown were quite positive, with the simulations accurately modeling the observed temperatures. These results were published in *Vadose Zone Journal* (Guiltinan *et al.*, 2020), being featured on the journal's cover. The results along with key lessons learned in experimental techniques and procedural methods were presented to the U.S. Nuclear Waste Technical Review Board in April 2019 and December 2020. Altogether, the shakedown provided the confidence to progress to BATS Phase 1a, the next step in a series of larger-scale experiments that will help the U.S. plan for the future of heat-generating nuclear waste, for which the disposal demand continues to grow.

BATS Phase 1a

Moving beyond experimentation in previously drilled boreholes, the researchers aimed to gather data in newer drilled-for-purpose boreholes. Drilling of the two new arrays was completed in April 2019, with each array consisting of a central borehole for the heater as well as surrounding boreholes for temperature sensors, acoustic emissions, electrical resistivity, and isotopic sampling. The unheated array of boreholes had nearly identical instrumentation to the heated array and was used as a control.

Between January and March 2020, an initial heater test (BATS 1a) in the new borehole arrays was conducted using the established 750W infrared heater from the shakedown. The results of this test were presented at the Waste Management Conference in March 2020 and documented in Kuhlman *et al.* (2020). However, follow-on phases (BATS 1b-1c) in which liquid and gas tracers will be incorporated will be conducted soon but are temporarily on hold due to restrictions associated with the pandemic.

Borehole permeability testing was conducted in June 2019 and in July 2020 by pressurizing the air behind an inflatable packer and while closely monitoring the pressure decay, as the gas flowed into the rock, proportional to the salt's permeability and the relative amount of gas and brine in the salt. Permeability is particularly important in terms of waste disposal safety because it is a measure of the ability of liquids—which could transport radionuclides—to move through the salt. For example, before the rooms creep closed and heal, the fractures within the damaged zone around the drifts are a potential pathway.



A view of the 3-D numerical model mesh showing the heated borehole location (large group of blue dots) and observation boreholes (single dots around it) at WIPP.

Internationally, other groups are also studying the behavior of salt related to radioactive waste disposal and have recently found that typical short-term laboratory experiments illustrating high deformation due to large differential stresses are not always indicative of field conditions (Bérest *et al.*, 2019). Understanding the mechanical processes going on at field-relevant conditions (low differential stress) is actually key for longer time frames, like the ones relevant in a repository. Different small-scale mechanisms lead to the creep observed in the field than during typical tests observed in the lab, making extrapolation from lab data to field applications problematic. This difference implies that creep would actually occur more rapidly in the field than first thought. This new understanding is being used to design more difficult but more relevant laboratory tests, to collect data, improve numerical models, and make better predictions about the behavior of salt.

Thus far, the data collected as part of BATS is aiding better understanding of thermal, chemical, hydrological, and mechanical processes going on in the damaged region surrounding a salt repository. Salt is one of the three media being generically investigated by the DOE-NE Spent Fuel and Waste Science and Technology (SFWST) program (along with granite and shale) because salt is self-healing and essentially impermeable to brine movement far away from excavations. The work being done as part of BATS aids in understanding the complex processes going on near the excavations in the damaged zone, where the ephemeral fractures in the salt allow brine and gas to flow.

"This work is important because it is what the repository looks like right now," Kuhlman said. "While the rooms in the repository will eventually close up to seal the waste away forever, predicting the behavior in the immediate future provides the initial conditions that allow us to assess the long-term performance of the repository and build confidence in our understanding of the problem."

Relevant DOE-NE reports from the SFWST program can be found on the online project hubs: sfwd.lanl.gov for Los Alamos and sandia.gov/salt for Sandia. Significant international collaborations are part of this research as well. Sandia has been involved in international collaborations on salt repository research with Germany for over 10 years. Additional international partners (the United Kingdom and the Netherlands) and U.S. laboratories (Los Alamos and Lawrence Berkeley) are also getting involved in this valuable international exchange of information. The more that interested research partners join in on the research effort, the better becomes our overall understanding of disposal options in salt.

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