SAND2022-3049C

ARMA 22–0296

Acoustic Emission Monitoring of Thermal Cycling in Salt at the Waste Isolation Pilot Plant

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This paper was prepared for presentation at the 56th US Rock Mechanics/Geomechanics Symposium held in Santa Fe, New Mexico, USA, 26-29 June 2022. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 200 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgement of where and by whom the paper was presented.

ABSTRACT: A series of field-based multi-physics observations were conducted as part of the Brine Availability Test in Salt (BATS) underground at the Waste Isolation Pilot Plant (WIPP), near Carlsbad, NM. Observations were made of brine production, temperature, electrical resistivity, acoustic emissions (AE), and gas/liquid tracer migration through salt around twin heated/unheated borehole arrays.

Here, we present AE results from thermal cycling experiments performed May – July 2021, during which the heater was pulsed several times followed by two longer heated periods. Sixteen AE sensors were installed in three parallel observational boreholes surrounding the central heated borehole. Observed AE demonstrate that heating and cooling cycles significantly impact salt behavior. AE rates increased during heating and increased further upon cooling. Average energy and frequency bandwidth also increased during heating and cooling of salt. Similar behavior was observed for each heating/cooling cycle, suggesting that temperature-enhanced salt healing may have eliminated any threshold loading associated with the onset of AE (i.e., the Kaiser effect). Locations of AE events remained centralized around the borehole. These results show that AE provide valuable information about the thermal behavior of salt, particularly that cooling of salt results in the highest AE behavior.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) outside of Carlsbad, NM is the nation's only active geologic repository for nuclear waste. Currently, WIPP is licensed to dispose of transuranic radioactive waste from defense activities. The US Department of Energy Office of Nuclear Energy's (DOE-NE) Spent Fuel and Waste Science and Technology program is pursuing generic research into multiple possible disposal media (i.e., salt, argillite, and crystalline rocks) for heat-generating waste from spent nuclear fuel. The DOE Office of Environmental Management (DOE-EM) that manages the WIPP site provides access to the WIPP underground DOE-NE work that is testing the behavior of the generic bedded salt under conditions relevant to spent fuel and high-level waste disposal.

Salt has almost unmeasurably low far-field permeability and porosity[1], but near mined excavations they are both elevated, i.e., the excavation disturbed zone (EDZ)[2]. Near access drifts, elevated temperatures from heat-generating waste can drive thermal pressurization of the salt and brine and migration of fluid inclusions within salt crystals[3,4]. The complex interactions between the thermal, hydrological, and mechanical processes going on in the salt EDZ are the focus of our testing. Brine has the potential to corrode waste forms and packages, transport dissolved radionuclides, reduce in-package criticality, and prevent porosity closure through pressurization[5]. It is crucial to understand the availably and composition of brine as initial conditions for performance assessment in a salt repository.

A series of borehole-based multi-physics observations were conducted, starting in 2020, as part of the Brine Availability Test in Salt (BATS) underground at the WIPP[6]. BATS is a DOE-NE funded collaboration between WIPP and Sandia, Los Alamos, and Lawrence Berkeley National Labs. BATS focuses on exploring brine availability as part of a wider investigation into the disposal of heat-generating radioactive waste in salt. In BATS, two identical arrays of horizontal boreholes were constructed; one heated array to investigate the effects of thermal cycling and one unheated array as a control (Fig. 1a, b). Each array has a series of observational boreholes centered around a gas-flow borehole. These observational boreholes monitor brine production, temperatures, electrical resistivity, acoustic emissions (AE), and gas/liquid tracer migration. The central borehole in the heated array contains a quartz infrared heater at 2.5 – 3 m depth behind an inflatable packer assembly to heat the

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salt; the unheated array has the same packer assembly without the heater (Fig. 1c).

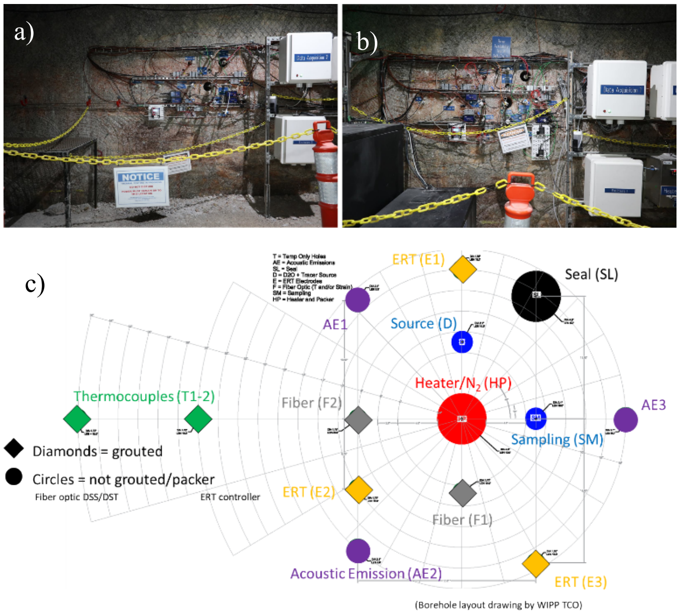


Fig. 1. a) Unheated borehole array. b) Heated borehole array. c) Layout of borehole array.

Here, we present AE results from the heated borehole array covering a series of heater tests during the second year of BATS, from March 8 to September 19, 2021, to investigate the effects of heating and cooling cycles on damage induced around a borehole. AE is generated in subsurface formation by cracking events and can be used as a proxy measurement for induced damage. Due to the low porosity of undamaged salt, induced fractures around an emplaced waste package represent the primary flow paths through the formation.

2. METHODS

Three 3-m boreholes dedicated to monitoring AE were installed in each borehole arrays, parallel to and surrounding a central heated borehole. AE boreholes were roughly 36 cm away from the wall of the central borehole, evenly spaced at 120° separation (Fig. 1c). Piezoelectric transducers were installed on a 3.05 m steel conveyance tubing through plastic centralizers attached to the tubing to maintain position during insertion and removal. Physical Acoustic Nano 30 AE sensors were inserted into a hole drilled into one of the arms of the centralizer and epoxied to a steel hemisphere (Fig. 2a). The arm of the centralizer pressed the steel hemisphere flush against the borehole wall, ensuring good acoustic coupling. Centralizers were installed at 30 cm spacing along the conveyance tubing (Fig. 2b). The heated array had 16 sensors; the unheated array had 8 sensors. Signals from AE sensors were amplified by 60 dB in-line Physical Acoustic pre-amplifiers. Data were recorded and processed using two Mistras Express-8 AE systems, one dedicated to each borehole array. An AE hit is defined as a response on a single channel where the signal amplitude exceeds a pre-determined threshold. This triggers the system to record a waveform. An AE event is defined as multiple AE hits in a short span of time that can be used to locate the origin of energy spatially in 3D. Hits were initially recorded using a 30 dB threshold, but this was later increased to 45 dB in postprocessing to control file size. Waveforms were bandpass filtered to 75-700 kHz. Processed and filtered data was input into ASC In-Site Laboratory seismic processing software for event location. Arrival times were picked automatically using the AIC method with manual corrections. Events were located using a simplex routine in a homogeneous-isotropic velocity structure. A minimum of 4 P-wave arrivals were necessary for location. Any mis-located events (e.g., events occurring in the drift) were discarded.

The quartz infrared heater in the central borehole of the heated array was pulsed several times during the observation period. On May 13, the heater was initially set to 120°C but shut off a few hours afterwards. The heater was restarted May 17 but it shut off after approximately 30 minutes. On May 18, the heater was restarted to 75°C. On May 24, the heater was increased to 90°C. On May 26, the heater was increased to 115°C. On June 16, the heater was intentionally turned off and allowed to cool. On June 29, the heater was restarted to 85°C. On June 30, the heater was raised to 115°C. On July 14, the heater was turned off. On August 25, the heater was set to 90°C and turned off the next day. The heater was turned on for 1.5 hours on August 30.

Gaps in the data occur on June 7, June 14, June 28 – July 6, July 21-22, August 24-25, and September 12-15.

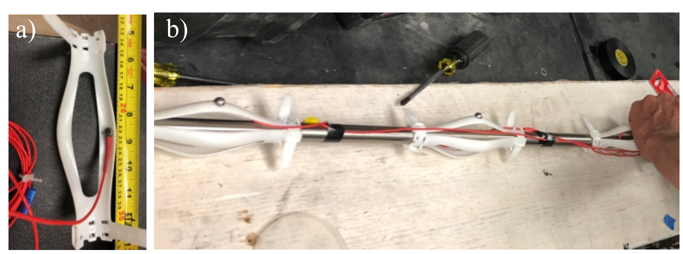


Fig. 2. a) Nano 30 sensor installed into plastic centralizer. b) Centralizers installed onto steel conveyance tubing.

3. RESULTS AND DISCUSSION

Over 740,000 hits were recorded over 6 months, resulting in over 8,800 located events (Fig. 3a, 4a). AE values reached an initial steady state rate from March to mid-May in the absence of thermal input. Background rates for hits were over 1,000 hits per day and 10 to 20 events per day (Fig. 3b, 4b). Cycling of the heater created surges in AE activity, as both hits and events increased by up to two orders of magnitude. Increasing temperature leads to an increase in AE, as seen on May 24 and 26. The greatest increase in AE rate are observed during cooling phases, as can be seen on June 16, and July 14. Heater pulses also result in increased activity due to combined heating and cooling (Fig. 3, 4). The largest AE activity is associated with the cooling period on June 16. This cooling period occurred after a long period of heating which would lead to the largest thermally disturbed volume of the considered time period.

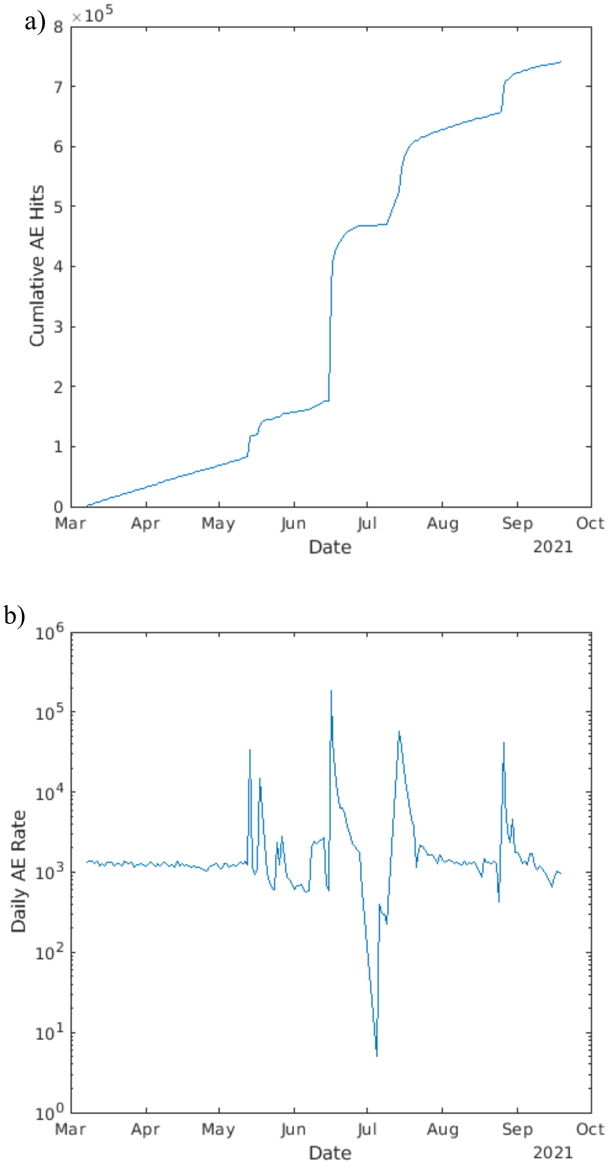


Fig. 3. AE hit activity in heated array. a) Cumulative AE hits through time. b) Daily AE hit rate through time (log scale).

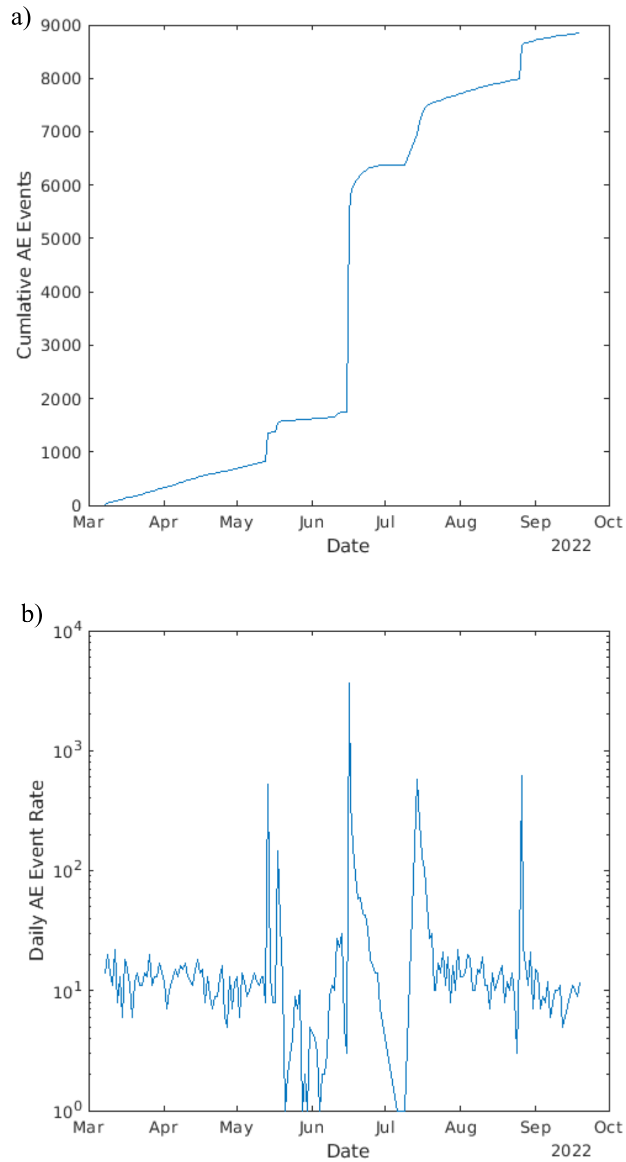


Fig. 4. AE events in heated array. a) Cumulative AE events through time. b) Daily AE event rate through time (log scale).

Determining the exact mechanism of damage creation can be difficult using AE. With smaller travel distances and limitation of compressive wave sensors, it can be difficult to invert focal mechanisms. A useful proxy for mechanisms is the ratio of counts per duration to rise per amplitude. This gives a measure of the energy of a signal compared to the length of waveform. Tension sources generate short bursts with higher energy inputs, while shear sources produce longer and more ringing waveforms. AE hits created by tension tend to group along the Rise/Amplitude axis, and hits created by shear mechanisms group along the Counts/Duration axis. Some hits from this observational period plot along the Counts/Duration axis, but most hits are along the Rise/Amplitude axis, indicating that most hits during thermal cycling are caused by tensile mechanisms.

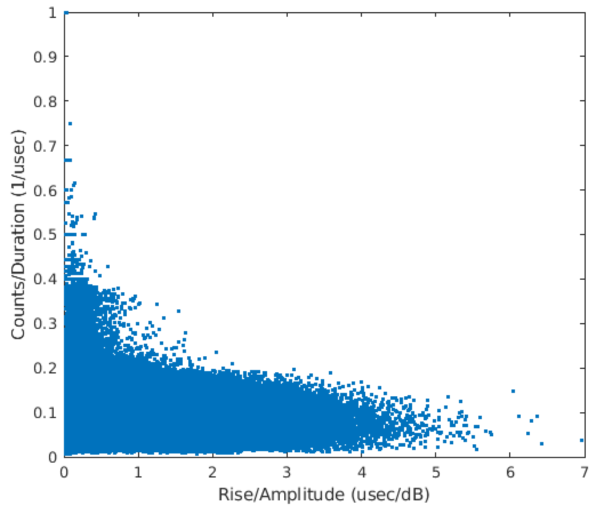
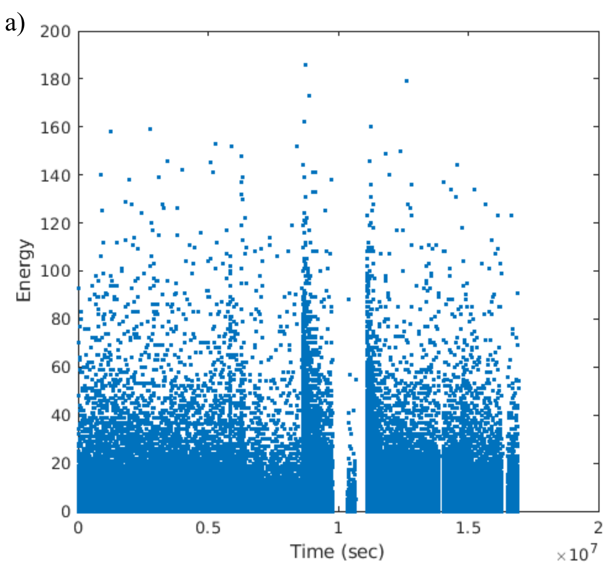


Fig. 5. Counts over duration versus rise over amplitude for AE hits.

Energy and frequency content increase for AE during periods of thermal cycling (Fig. 6). Large increases in energy can be observed for cooling periods, with smaller increases associated with heating phases. Broader frequency content follows a similar trend with heating and cooling. The increase in activity is associated with an increased number of hits with average frequency content from 250 to 450 kHz (Fig. 6b).



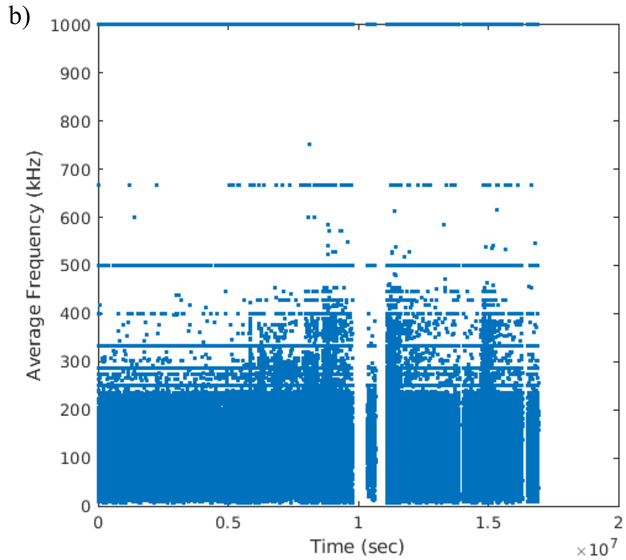


Fig. 6. a) Energy (10 µvolt-sec/count) versus time for AE hits. b) Average frequency versus time for AE hits.

Located events form a broad cloud around the central borehole (Fig. 7). Events are contained within a 5 m by 5 m square area that extends up to 10 m deep into the salt.

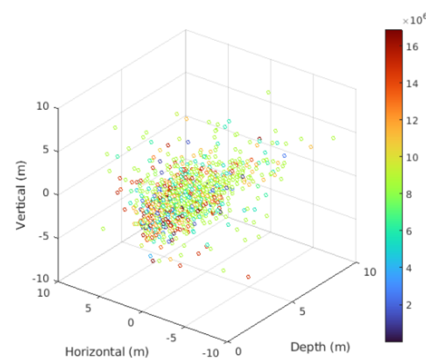


Fig. 7. Located AE events. Color bar shows elapsed time in seconds.

These observations demonstrate that thermal cycling in salt results in large numbers of generated AE and potentially large numbers of induced fractures. We have seen AE increases upon heating, as salt crystals around the wellbore respond stress increases from thermal expansion. We have also seen that the greatest activity is associated with cooling, as salt grains contract each other. The rise time to energy ratio of AE waveforms indicate the most hits are generated from tensile fracture events. Cracks are likely opening around the borehole during cooling phases. The heating of salt results in cracking but would not result in increased porosity due to increased confinement from constrained thermal expansion. Cooling results in large numbers of tensile events that may increase permeability into the formation.

Located events show that damage inducing events remain close to the wellbore. Events are contained in a 5 m × 5 m

× 10 m box, suggesting that fracture-induced porosity will not extend far into the formation; most events are associated with cooling periods.

This dataset represents the second year of thermal cycle testing in the BATS array, previous tests were conducted in 2020. There are some indications that previous testing has affected the 2021 dataset. This dataset had a similar number of AE hits for a timespan for the May to June thermal test that the 2020 testing had for a thermal test from January to February, despite 2021 testing having double the amount of AE sensors than the 2020 test. Similar heated periods should have resulted in similarly sized thermally disturbed zones around the borehole. The reduced activity in 2021 may be due to the Kaiser effect, a phenomenon in metals where AE are not observed in reloads until the previous maximum load is reached (Holcomb, 1993, Lavrov, 2004). AE begins immediately on heating/cooling in subsequent cycles, suggesting that heated salt can heal previously induced damage around the borehole and diminish the Kaiser effect.

We have studied thermal cycling imparted by infrared lamps that allow for rapid heating and cooling of the formation surrounding a borehole. For heat generating waste, thermal load would be applied quickly and be maintained for long periods of time. Cooling would be a gradual process as radioactive material slowly decays (e.g., Sr-90 half-life is 28.8 years). Elevated temperatures over decades would allow the salt to creep and heal fractures from thermal loading. Most AE hits and events we observed are associated with rapid cooling, this may not apply to the conditions in a repository but is necessary for understanding field datasets collected from electric heaters.

4. CONCLUSIONS

We have presented AE results from thermal cycling tests occurring from May to September 2021 as part of the BATS field investigation at the WIPP site. We have seen that heating the salt results in AE activity with increased energy and frequency content. We have also seen that cooling the salt results in greater AE activity than heating. The ratio of waveform rise time compared to duration indicate that the majority of AE resulted from tensile fracture mechanisms, that may indicate the presence of fracture induced porosity around the borehole. Located events show that activity is occurring in a small area around the heated borehole.

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This paper 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.

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