Thermally induced acoustic emissions in salt at the Waste Isolation Pilot Plat (WIPP)

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ABSTRACT:

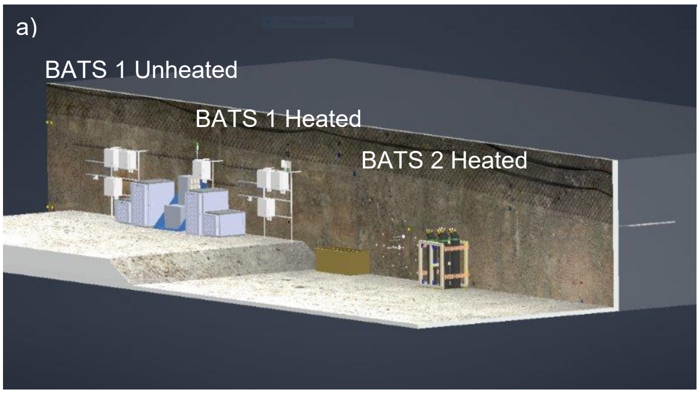
Heat-generating nuclear waste in salt-based repositories can act to modulate local porosity, permeability, and brine availability. Understanding the availability and flow of brine through salt deposits is instrumental in predicting the safety of nuclear waste repositories. Brine can facilitate the transport of radionuclides offsite, corrode waste packaging, and inhibit the closure of the repository. To address these challenges, a heated borehole array is established as part of the Brine Availability Test in Salt (BATS) at the Waste Isolation Pilot Plant (WIPP) (Figure 1). Four boreholes are dedicated to monitoring acoustic emissions (AE) as a proxy for thermally induced fracturing that may alter porosity, permeability, and deformation within the repository. Fracture response depends on stress variations, pore pressure, fluid chemistry, temperature, rock behavior, and in situ anisotropy. To measure the spatial and temporal evolution of thermally induced fracturing, we locate each AE event during heating and cooling to map fracture events and fracture networks. Results indicate that AE provide valuable information on temperature dependence of damage accumulation and fracture growth, demonstrating that the cooling phase is more likely to create fractures that may change near-wellbore hydrology.

1 Introduction

The Waste Isolation Pilot Plant (WIPP) outside of Carlsbad, NM is the nation's only active deep geologic repository for nuclear waste. Currently, WIPP is licensed to dispose of transuranic waste. As part of the US Department of Energy Office of Nuclear Energy (DOE-NE) Spent Fuel and Waste Science and Technology program strategy, efforts to develop a repository for heat generating nuclear waste are pursing generic research in multiple disposal media (i.e. salt, argillite, and crystalline rocks). Access to the WIPP site for investigations into the behavior of generic bedded salt is managed by the DOE Office of Environmental Management (DOE-EM).

Salt is an excellent candidate for waste storage due to its inherent low porosity and permeability (Beauheim & Roberts, 2002), and ability to creep on repository timescales. One potential issue with installing a repository in salt formation is the resulting excavation disturbed zone (EDZ) from mining drifts, shafts, and caverns (Blanco-Martin et al., 2018) which open fractures and potential fluid pathways near drifts and boreholes. Brine inclusions in salt crystals and water from hydrous minerals have the potential to migrate towards heat generating waste, where brine could corrode waste forms and packages, transport dissolved radionuclides through the EDZ, reduce in-package criticality, and prevent porosity and cavern closure through pressurization (Kuhlmna & Seougian, 2013). Here, we focus on brine movement in response to thermal pulses in the EDZ.

A series of ongoing borehole-based multi-physics observations was initiated in 2020 as the Brine Availability Test in Salt (BATS) in the underground at WIPP (Kuhlman et al., 2021). BATS is a multi-laboratory project funded by DOE-NE, with PIs from Sandia National Laboratories, Los Alamos Laboratory, and Lawrence Berkeley National Labs. BATS focuses on exploring brine availability in the context of generic disposal of heat generating radioactive waste in bedded salt. BATS initiated with Phase 1, where identical arrays of horizontal borehole were constructed with multiple types of instrumentation boreholes (Kuhlman et al., 2020). One array contained a heated central borehole, the other contained an unheated borehole as control. Three heater tests were conducted in the first phase (Kuhlman et al., 2021). In 2021, BATS Phase 2 began with the decommissioning of the heated array and construction of a new heated borehole array 6.1 m away from the Phase 1 heated array (Figure 1a) (Kuhlman et al., 2022). In the new heated array, the central heated borehole is 3.82 m deep into the formation with a 1250-watt quartz lamp heater. The new heated array contains boreholes for liquid sampling, pressure tests, permeability measurements, tracer movement, thermocouple-based temperature measurements, fiber-optic based temperature and strain measurements, electrical resistivity, and cement-based strain measurements around this central borehole (Figure 1b). The unheated array has continued to record data since 2020, but these datasets are presented elsewhere. Seven heater tests have been conducted during BATS Phase 2 – 2a, 2b, 2c, 2d, 2e, 2f, and 2g (Kuhlman et al., 2024).



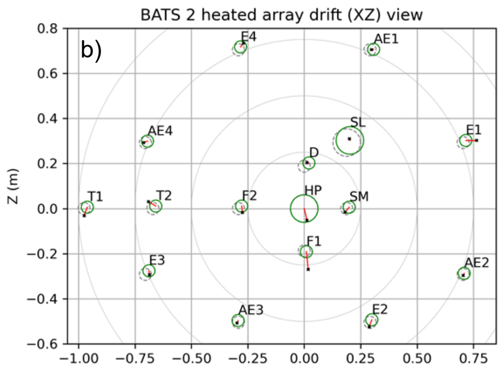


Figure 1. a) BATS Phase 1 and Phase 2 borehole arrays. b) Layout of BATS Phase 2 heated borehole array.

Here, we focus on emitted acoustic emissions (AE) during heater event 2e, conducted from November 16 to December 7 2023, to investigate the effects of heating and cooling around the central heated borehole. Heater event 2e occurred ~8 months after the previous heater tests, allowing time for the salt to creep and heal. The heater controller was set to 140 °C for the 3-week duration. AE is generated by cracking events in the formation and can be used as a proxy measurement for induced damage. Induced fractures in the subsurface are the primary flow path in otherwise impermeable salt, and located AE can be used to identify the extent of damage with heating.

2 Methodology

Four boreholes dedicated to AE were installed at depths up 3.35 m into the formation for BATS Phase 2. AE boreholes are separated by ~90° around the heated central borehole, arranged to allow for a clear travel path from the central borehole to the AE boreholes (Figure 1b). Physical Acoustic Nano 30 AE sensors were mounted to steel conveyance pipe using kwik-

ZIP plastic centralizers for installation and removal of sensors during testing and to ensure consistent sensor orientation (Figure 2). Sensors were inserted into a hole drilled into the arm of plastic centralizers and epoxied to a steel hemisphere that acted as a wave guide. The hemisphere was oversized compared to the sensor, so the centralizer arm would push the hemisphere against the borehole wall after installation (Figure 2a). This allowed for consistent coupling between sensors and the formation without loading the sensor. Coupling would improve for a brief time after installation as the hemispheres would adjust, creeping slightly into better contact with the salt. At the time of heater event 2e, the AE sensors had been installed for over a year and coupling would be consistent throughout the test. Plastic centralizers were affixed to the conveyance pipe with a screw to maintain inter-sensor spacing during installation and removal (Figure 2b). A total of 18 sensors were installed in the 4 AE boreholes, but only 16 channels were used during testing.

Data were recorded and processed using a Mistras Express-8 AE system with a total of 16 channels. Signals from the sensors were amplified by Physical Acoustic 2/4/6 in-line preamplifiers at 40 dB amplification. Threshold for recording was set to 28 dB and bandpass filtered at 100 to 700 kHz averaged frequency. An AE hit is defined as a response on a single channel where the signal amplitude exceeds the 28 dB threshold. An individual waveform is recorded for every hit, recording 250 μsec before the threshold crossing and 750 μsec after the initial crossing at 10 MSamples/sec. Neighboring instrumentation with electrical interference and mining activity created significant noise issues during data collection. Data are post-processed using a partial power frequency filter, where the energy content in the 10 to 250 kHz frequency band must be greater than or equal to 50% of the total energy of a recorded waveform to be analyzed, otherwise the waveform is discarded. An AE event is defined as multiple AE hits in a short span of time that can grouped and located to identify the origin of the energy in the formation. Events are located using In-Site Lab seismic processing software from Applied Seismology Consulting. Events require a minimum of 4 hits for location. Arrival times are picked using an AIC auto-picking algorithm and manually corrected. Events were located using a simplex algorithm with an isotropic velocity structure. Any event occurring outside of a 10 x 10 x 10 m cube around the central borehole were discarded.

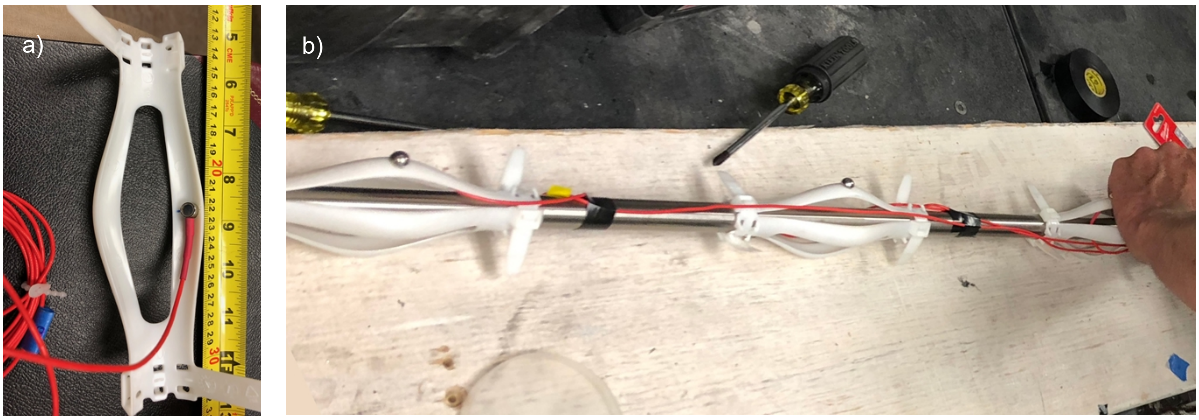


Figure 2. a) Nano30 acoustic emission sensor installed into plastic centralizer. b) Centralizers and sensors installed onto steel tubing.

Heating the central borehole to 140 °C initiated on November 16, 2023 at 09:42 and continued until December 7, 2023 at 11:37. This dataset includes the behavior 2 weeks prior and 3 weeks post heating. Gaps in the data occur from December 4-11.

3 Results and Discussion

A total of 327,356 AE hits were recorded after initial recording and partial power frequency filtering from the timespan of October 31, 2023 at 00:15 to January 2, 2024 at 11:07 (Figure 3a). A total of 9,771 events were located in a 1000 m^3 around the central borehole (Figure 4a). AE reached a constant background level of ~3100 hits/day and ~90 events/day from October 31 to November 15 (Figure 3b, 4b). At the onset of heating at 09:42 on November 16, AE activity greatly increased. The first day of heating saw over 71,000 AE hits and 2,847 events. Daily activity remained elevated but started to decay throughout heating. By November 21, AE activity was below background levels prior to heating. Activity remained depressed, daily AE hits were less than 2000 hits per day and 30 events per day for the last week of heating. The cessation of heating and the onset of cooling at 11:37 on December 7 increased AE activity. The first part of cooling is missing from the data, but AE rates remain elevated for an extended period. 4 days after the heater change on December 11, AE daily rates are over 20000 hits and 700 events. AE activity remained above background levels for the remainder of the 3.5 weeks of investigation (Figure 3b, 4b).

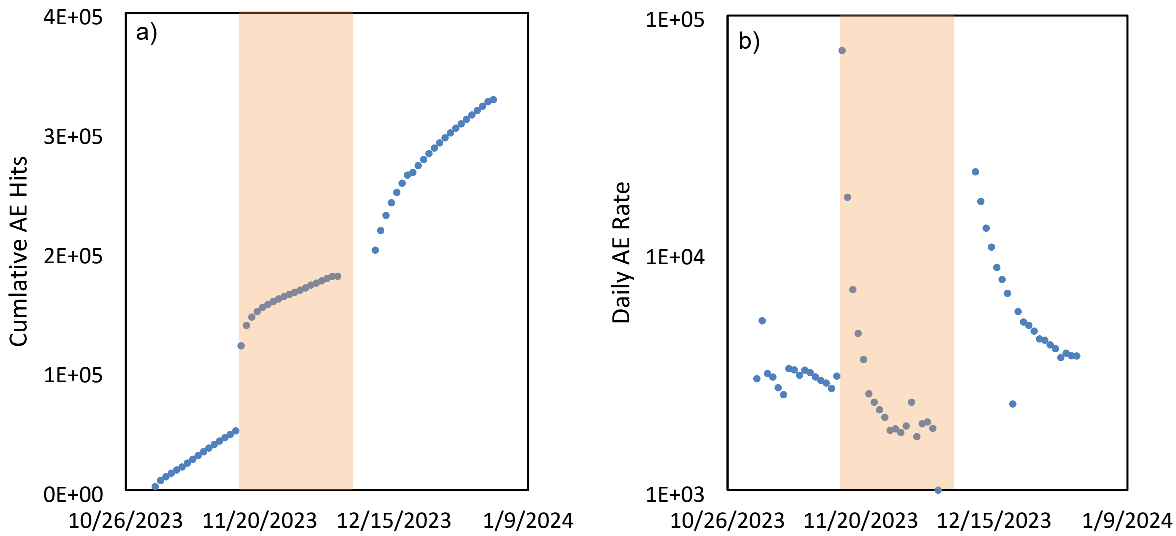


Figure 3. a) Cumulative AE hits for heater event 2e. b) Daily AE hit rate for heater event 2e (log scale). Heated period marked in orange.

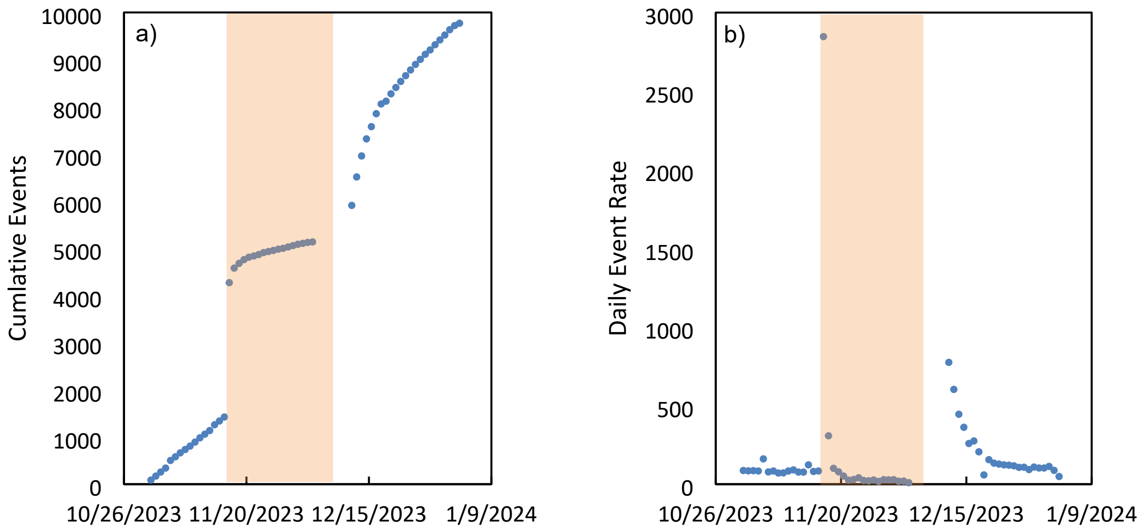


Figure 4. a) Cumulative located events for heater event 23. b) Daily located event rate for heater event 2e.

Determining source mechanisms based on AE can be difficult. Small travel distances, single channel compression sensors, and large volumes of data make it difficult to invert for focal mechanisms. The ratio of AE hit energy to length is often used to identify shear versus tensile sources. Shear sources release lower amounts of energy over longer durations, while tensile source release higher amounts of energy over shorter time. AE hits are plotted on axes of counts/duration versus rise/amplitude. Counts are defined as the number of threshold crossing per waveform, duration is defined as the length of the waveform, rise is defined as the time to peak, and amplitude is the maximum value. Tensile sources plot along the rise/amplitude axis indicating increasing energy with short duration, while shear sources plot along the count/duration axis, indicating lower energy with increasing durations. Most events are near the rise/amplitude axis, indicating that most hits are associated with tensile sources and opening mode fracture mechanisms (Figure 5). This type of cracking would be the associated with changes in porosity and permeability in the near field.

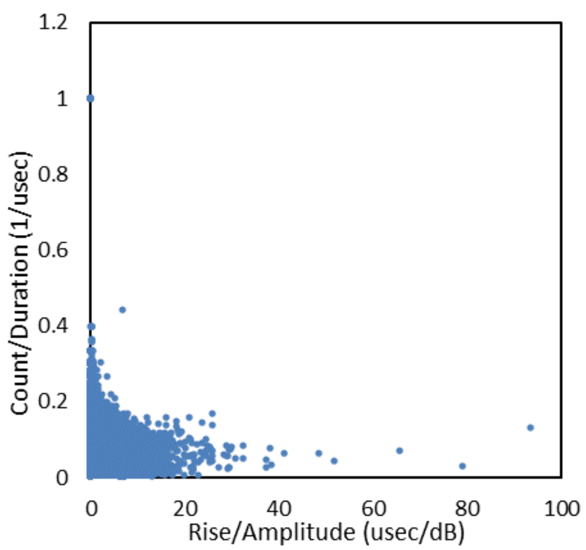


Figure 5. Counts over duration versus rise over amplitude.

The average signal level (ASL) is a measure of the continuously varying amplitude that has been averaged over a 500 msec time window per hit. Like AE hit and event activity, ASL depends on heating/cooling cycles. With the onset of heating, there is a brief increase in ASL, but levels soon drop off to below background levels (Figure 6a). During heating, signals lack larger values seen during background times, and seemingly the lower signals values decrease as well. During cooling, larger ASL levels can be seen that exceed the quiescent period during heating and a greater number of 10+ dB signals compared to background levels. The low value ASL signals seen during heating are also absent during cooling (Figure 6a).

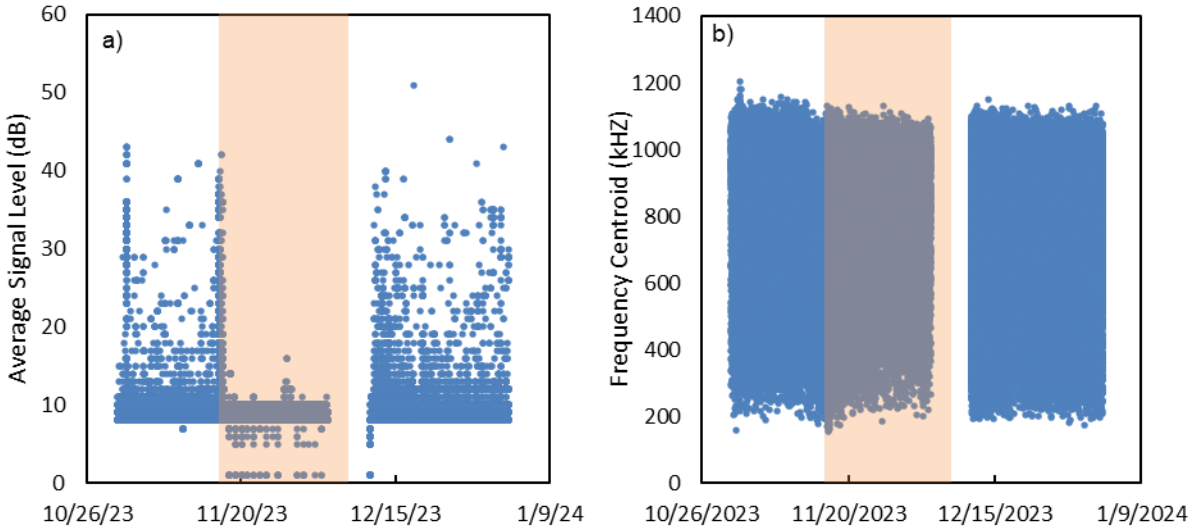


Figure 6. a) Average signal level for AE hits over time. b) Centroid of fast Fourier transform of AE hits frequency.

The frequency centroid is derived from fast Fourier transforms on recorded waveforms and represents the average frequency based on the energy of frequency bands. Here, the frequency range depends on the thermal state of the material (Figure 6b). There is an observable increase in the amount of low frequency events at the onset of heating that subsequently decays and leads to less low frequency content towards the end of the heating period. The high frequency content also briefly increases at the onset of heating before decreasing to below background levels at the end of heating (Figure 6b).

Located events cluster around the heated borehole, primarily within the AE boreholes and shallow depths in the formation as expected (Figure 7). Locations have a slight bias towards AE borehole #3. Background events are low with only occasional events outside the radius of the AE boreholes. At the onset of heating at ~1.41×10^6 seconds, the event rates surge. At the onset of heating, AE events are clustered within the AE boreholes. After 1 hour, events have spread beyond the boreholes and away into the formation. There is a cluster of events that extends downward in a quasi-linear feature. The widespread distribution of events is a short-lived feature, as events return to AE borehole radius by the start of November 17 and remain close to the heated borehole during the quiescence period (Figure 7). The onset of cooling is missing from the data, but the located cooling data shows events mostly located within the AE boreholes with a higher likelihood of occurring outside the boreholes when compared to background levels.

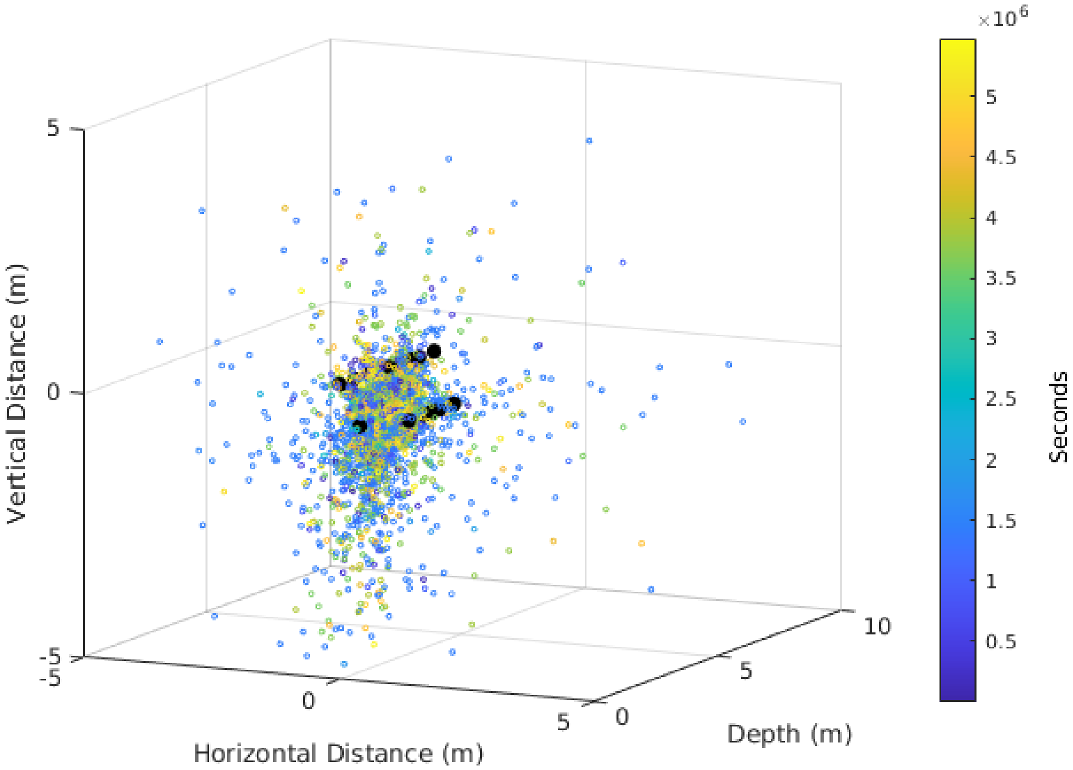


Figure 7. 3D locations of AE events. Black spheres represent AE sensor locations. Color bar shows elapsed time in seconds.

A detailed look at heater event 2e shows a clear impact on thermal cycling on recorded AE. The onset of heating creates a spike in AE activity, increasing the number of hits and events, creating events with larger ASL and broader frequency responses (Figure 3, 4, and 6). Cooling has a similar but more pronounced effect to heating, with larger increases in rates and signal levels (Figure 3, 4, and 6). There is a sharp difference between steady state behavior between heating and cooling. Activity surges at the onset of heating and decays such that AE rates and signal levels are below background levels within 4-5 days (Figure 3, 4). Events briefly expand away from the heated borehole and quickly collapse to the near borehole vicinity (Figure 7). The array, once equilibrated, is quieter at temperature than background levels at ambient conditions (Figure 3, 4, and 6). This indicates that cracking mechanism are suppressed at elevated temperatures. This could either indicate that volumetric expansion of salt with temperature has acted to stabilize the borehole array and reduced deformation, or that elevated temperatures have changed the active deformation mechanisms in the salt from a predominantly tensile cracking mechanics to a plastic mechanism that may not generate AE. Either mechanism would indicate that the generation of cracks associated with fluid pathways is suppressed once the salt equilibrates at temperature. Cooling is associated with elevated levels of AE activity that remain above background for the duration timescale of this paper. These elevated levels of AE and likely tensile mechanisms may indicate increases in near-field permeability around the central borehole (Figure 3-6).

The conditions of these borehole tests help illuminate potential issues in establishing a salt-based repository for heat generating waste. Emplacing hot waste would apply a rapid thermal load to the surrounding salt formation and maintain elevated temperatures for long periods of time. The AE results here show that potential opening mode fracture spike with rapid increases in temperature, which would be a concern for containment. This behavior would also be short-lived and fracturing would quickly decrease with thermal equilibration. The behavior of the borehole arrays equilibrated in less than a week, making it unlikely that engineered barriers and seals around waste packages would fail in such a short amount of time. Large AE activity is associated with the rapid onset of cooling, but the decrease in temperature in a repository would be controlled by radioactive decay and may not match the conditions of this experiment.

4 Conclusions

Acoustic events from heater event 2e from BATS Phase 2 have been analyzed to better understand the potential formation of opening mode cracks and fluid flow pathways associated with the emplacement of heat generating radioactive waste in a generic salt repository. From November 16 to December 7, 2023, the borehole wall of the central borehole was heated to about 140 °C. Acoustic emissions were monitored on 16 channels from observation boreholes starting in 2022, shown here are AE data October 31, 2023 to January 2, 2024 to capture background behavior at ambient conditions and post heating equilibration time. AE activity surges with the onset of heating, with increased rates and stronger signals. The increase in activity quickly diminishes, and within 5 days activity is lower than ambient background levels. Activity increases with the onset of cooling and remains elevated for the observational period. For both heating and cooling, AE events remain within the vicinity of the wellbore. Characteristics of individual AE hits suggest that the mechanisms are primarily opening mode, indicating that near field permeability may be enhanced at the onset of heating, but the phenomena would be short lived. The rapid onset of cooling may result in longer lasting changes to near field permeability, but cooling in a repository setting is expected to be gradual from radioactive decay processes.

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