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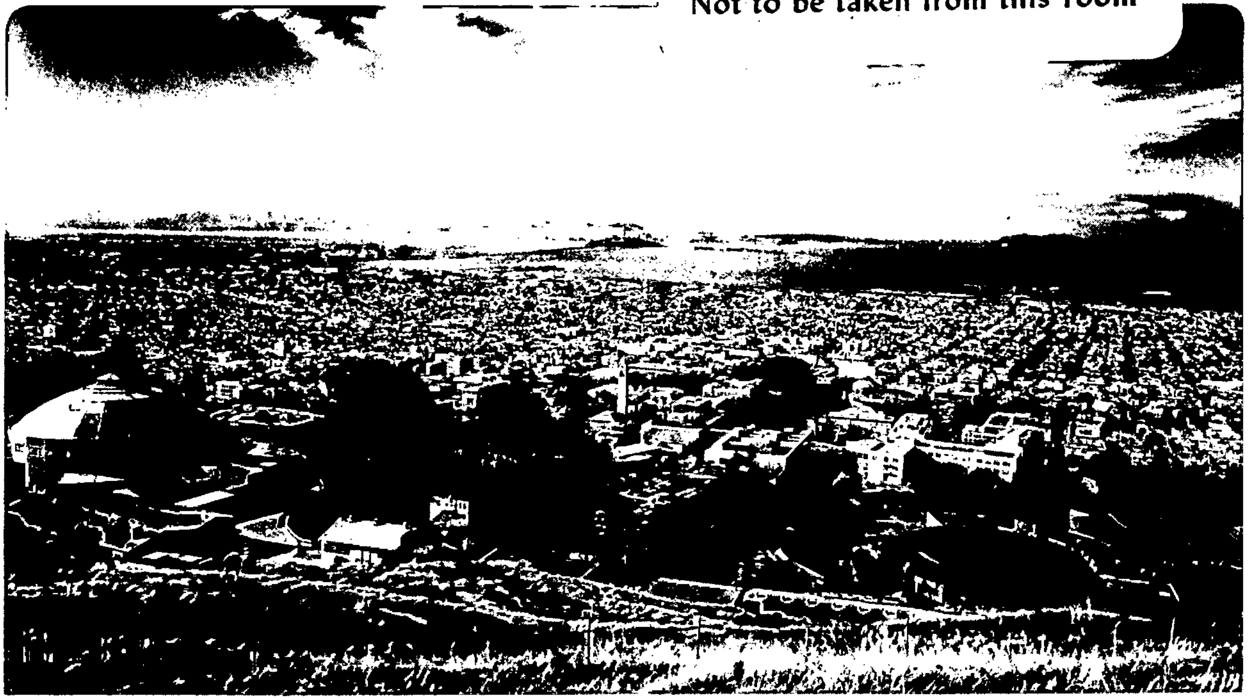

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DISCLAIMER

THE APPLICATION OF MODERN SEISMOLOGICAL METHODS TO ACOUSTIC EMISSION STUDIES IN A ROCK MASS SUBJECTED TO HEATING

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ABSTRACT

Modern seismological methods developed to study microearthquake phenomena are being utilized in an acoustic emission (AE) experiment designed to investigate the mechanical behavior of hard crystalline rock subject to heating by high-level nuclear waste. The sensors consist of a fifteen-station, three-dimensional array (dimensions: 50 m x 20 m x 10 m) of accelerometers surrounding eleven canisters of spent nuclear fuel and six electrical heaters simulating spent-fuel canisters. The canisters are arranged in a linear array in the Climax stock at the Nevada Test Site, at a subsurface depth of 420 m. The data are digitized and analyzed in situ by an Automated Seismic Processor (ASP) developed for microearthquake studies, using a 15-channel transient waveform recorder system to convert from the high-frequency (1kHz to 10khz) AE events. Velocity and attenuation control within the rock mass is provided by a controlled-pulse piezoelectric source located centrally within the sensor array.

In this paper are discussed the theoretical basis for studies of the AE source characteristics, a description of the instrumentation employed and a review of results obtained over the first 18 months of operation of the facility.

INTRODUCTION

Among the factors to be considered in the interaction between nuclear waste and the host rock in an underground repository are the response of the rock to changes in stress as a result of mining drifts, or to thermal loading from the waste, the effects of radiation, the influence of drift backfilling, and the role of potential subsequent subsidence above the repository. Significant stress or strength changes in the host rock may induce fracturing with consequent increase in fluid permeability and concomitant accessibility of waste to groundwater. Of concern also are fractures in the host rock, induced by mining or naturally occurring, that have remained undetected by explor-

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atory boreholes or the drifts themselves. These factors represent potentially serious problems in assuring the long-term stability and integrity of a repository.

Full-scale experiments conducted underground are required to investigate the relative importance of the various factors tending to compromise integrity of the repository. Such experiments, incorporating different design geometries, temperatures, and radiation levels, must be performed in rock types representative in composition, permeability and stress conditions of planned in situ repository conditions. Measurements must be made at sensitivities that permit detection of what may prove to be very long-term processes.

A potential monitoring method, possessing the natural advantage of concentrating these expected long-term effects into less frequent but much larger transient effects, is based on the observation of acoustic emission (AE) of microearthquake (ME) phenomena. Differing in only time and distance scales (AE involves kHz frequencies and cm distance; ME involves Hz and km), both phenomena represent strain relief through discrete faults or failure events within the respective media. Well-established methods [Johnson, 1979] exist in ME seismology for locating and describing the nature of such sources of elastic wave radiation. These methods, with proper scaling, might be expected to be applicable to the investigation of AE events from an underground repository. This study is addressed to the investigation of the applicability of ME seismology techniques in AE to monitor the integrity of an underground waste repository.

Few studies of seismic activity on this scale have been reported. In one such experiment at the Stripa iron-ore mine in Sweden, conducted by the Lawrence Berkeley Laboratory (LBL) of the University of California and the Swedish Nuclear Fuel Safety Agency (KBS), electrical heaters in granite were employed to study thermal stress effects. AE studies were started well after heater turn-on, and only one sensor was used. However, considerable AE activity was still observed during the later stages of the heating phase, and activity increased during the initial stages of the cool-down period (Paulsson et al, 1980).

Two mechanisms are generally thought to be responsible for AE activity induced by heating: the contrasting thermoelastic behavior of different minerals within the rock and the thermal gradient effect due to uneven heating. Yong and Wang (1980a) investigated AE from air-dried Westerly granite at atmospheric pressure and over the temperature range 20°C to 120°C and observed an abrupt increase in AE at a threshold temperature of approximately 70°C. They found that above this threshold temperature the rate of AE depended strongly upon the rate of heating. In further experiments Yong and Wang (1980b) compared AE from specimens of Westerly granite air-dried and water-saturated. In a dry specimen, the rate of AE was observed to be higher than for one water-saturated at the same temperature and heating rate. This behavior was attributed to differences in thermal gradient within the specimen, this being smaller in the water-saturated than the dry specimen.

It is not known what mechanisms will predominate in a scaled-up version of these heating processes. Differential thermal expansion will undoubtedly be important. The scale on which this will occur is, however, unclear, although King and Paulsson (1981) have observed the same effect on a heated 300 mm x 300 mm x 600 mm block of granite at the Stripa mine site during acoustic velocity crosshole experiments. Finally, the effect of uneven cooling due to partial water saturation of heterogeneous material of uneven geometry may also play an important role in the fracture process.

THE CLIMAX REPOSITORY EXPERIMENT

A unique opportunity to investigate many of the problems associated with the storage of nuclear waste has been provided by the spent fuel test being carried out by the Lawrence Livermore National Laboratory (LLNL) of the University of California in the Climax stock at the Nevada Test Site (NTS). The general objective of this full-scale experiment is to test the feasibility of short-term (five years) storage of spent-fuel assemblies from commercial reactors at a reasonable depth in a crystalline igneous rock, followed by retrieval of the assemblies. A detailed description of the experiment is provided by Ramspott et al (1979).

The layout of the experimental facility, 420 m subsurface, is illustrated in Figures 1 and 2. The center drift provides the storage area for a linear array of eleven spent fuel assemblies and six electrical heaters. The waste canisters and heaters are located in steel-lined vertical holes on 3 m centers. The electrical heaters are included to study the effects of heating with and without nuclear radiation. The two side drifts each contain ten smaller electrical heaters on 6 m centers. These heaters are used to produce a temperature field in the canister drift and adjacent pillars that will simulate the conditions in a large repository. Rock temperature, stress, and displacement are monitored continuously with an array of 430 thermocouples, 18 vibrating-wire stressmeters, 116 extensometers, and 34 convergence heads.

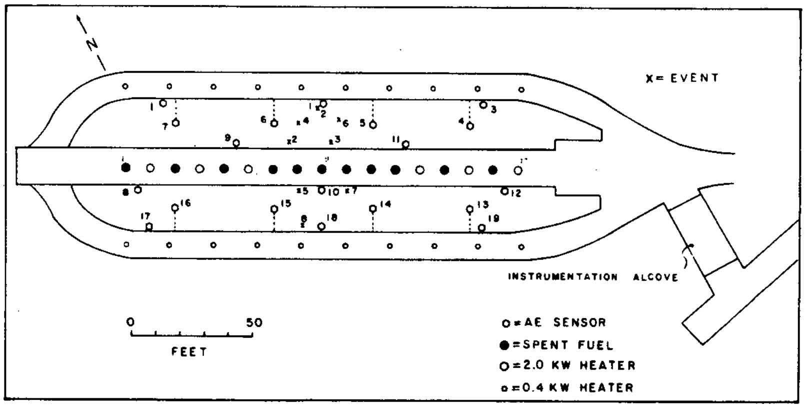

Figure 1. Plan view of Climax experiment.

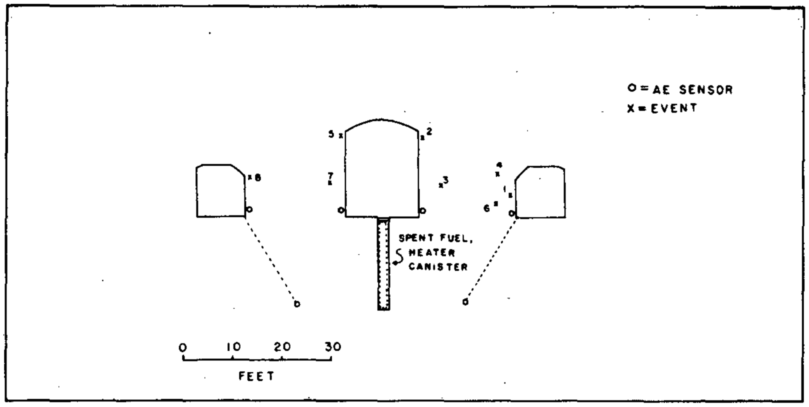

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Figure 2. Cross section of Climax experiment.

The Climax Stock is a composite granodiorite and quartz monzonite. It is an intrusive body bounded on the east and west by faults, with a surface exposure of 4 km^2 and widening to an estimated maximum extent of 100 km^2 at several kilometers depth [Maldonado, 1977]. The Climax Stock was the site of two nuclear explosions, HARDHAT 5kt, 1962, and PILEDRIVER 62kt, 1966, centered approximately 210 and 460 m respectively from the canister drift. Borg (1970, 1973) has determined that pervasive fracturing associated with the nuclear explosions did not extend to the present experimental area. The location of the permanent water table at the Climax stock has not yet been defined precisely, because of the very low permeability of the granite. At a subsurface depth of 420 m, the rock appears to be unsaturated but not dry. Several water seepages are observed throughout the workings, but the majority of holes drilled for the AE sensors are still dry, even after 18 months. The behavior is not unusual of that observed below the water table in very tight rock masses.

APPLICATION OF SEISMOLOGICAL METHODS TO REPOSITORY MONITORING

Over the past fifteen years, seismologists have paid considerable attention to detailed source descriptions [Johnson, 1979]. Both static and dynamic source characterization have been addressed in the literature. Of the static descriptions, the semi-empirical approach of Brune (1970, 1971) is the most widely applied. In this method, three independent source parameters from the frequency spectrum of either the compressional or shear wavetrain are estimated. Brune's hypothesis is that the low-frequency level of the spectrum is a measure of the strength, or seismic moment, of the source, and that the high-frequency character is determined by the source dimension. Two events with identical low-frequency levels but with differing high-frequency content would imply different stress drops. Pollock (1980) reports the application of spectral analysis methods to the field of acoustic emission. Efforts to date appear to have been towards defining different AE source processes from the frequency content of the signals. Jax (1974) reported that even for sources with frequency content as high as 500 kHz, there was a correlation between material properties and source duration. Wolitz et al (1978) have been able to categorize types of failure in fiberglass from spectral content. Spectral data have also proved useful in discriminating signals from noise, and in studies of plastic versus brittle deformation [Pollock, 1980].

Other techniques used in earthquake studies include the fault plane solution [Byerly, 1928] and "b-value" determination. AE studies appear generally to have ignored the fault plane approach to determine the principal stress direction and geometry of the fracture plane. However, AE researchers have employed b-value studies ($\log N = a - bM$; where N = cumulative number of events and M = magnitude of events) to infer particle size and ductability of material [Pollock, 1980]. On the other hand, earthquake studies using the b-value to characterize the mode of failure have generally concluded that the b-value appears to vary with the distribution of the applied stress field and with the homogeneity of the material [Mogi, 1962; Scholz, 1968; Wyss, 1973].

For the experiment described here for monitoring AE within a nuclear waste repository, several different stress field perturbations will exist. The fairly uniform lithostatic stress field due to overburden will be affected by the mine geometry to produce a heterogeneous stress field. Thermal effects, such as those due to cool water seeping into warm areas, will superimpose an additional stress field. Radiation degradation and heterogeniety of the rock mass will provide other factors influencing failure rates and mechanisms. The Climax AE experiment is designed to isolate these factors, if possible, and to estimate their relative significance.

It is intended to correlate the AE results with the available stress, strain, and temperature data to infer fracture and material properties. The location and size of events relative to the stress perturbations will bear on future repository design with respect to the spatial density and configuration of canister holes and mine openings. By analyzing the manner and rate of energy release, information on the suitability of granite as a repository material will be evaluated.

In addition to the questions already addressed, there remains the problem of overall mine stability and safety. There has been limited success using AE to predict failure in metals and alloys [Pollock, 1980]. Considerable effort has been directed towards predicting rock bursts and roof falls in mines, however, with better results [Blake et al, 1974; Brady, 1978]. Common methods applied in AE studies involve monitoring the variations in source locations, the number and amplitude of events, the time between events, event duration, energy release, and spectral content. By far the most generally used of these techniques have been event location and counting methods [Hardy and Leighton, 1980]. The reason for this is mainly because the available equipment is incapable of the fast on-line processing required for real-time sophisticated analyses. The principal aim of this study will be to characterize the AE activity in more complete terms relative to the continuing physical processes, using microearthquake methods scaled to the Climax experiment.

THE CLIMAX AE EXPERIMENT

The equipment selected to monitor AE activity includes accelerometers, charge amplifiers, and a 15-channel transient waveform recorder system interfaced to a microprocessor-based Automated Seismic Processor (ASP). The specifications of the equipment, the frequency response of the system, and a system diagram are listed in Table 1 and are shown in Figures 3 and 4.

TABLE 1

Columbia 5002 Accelerometer	
Sensitivity	13 pcoul/g
Freq. Response	2 Hz to 10 kHz, ± 5%
Resonant Freq.	50 kHz
Capacitance	850 pF
Output Resistance	2 x 10^{10} ohms
Columbia 9021 Charge Amplifier	
Source Impedance	Capacitive device, 500 pF max
Charge Gain	100 mv/pcoul (40db)
Output Impedance	125 ohms
Freq. Response	1 kHz to 10 kHz, ± 5%

g = acceleration of gravity

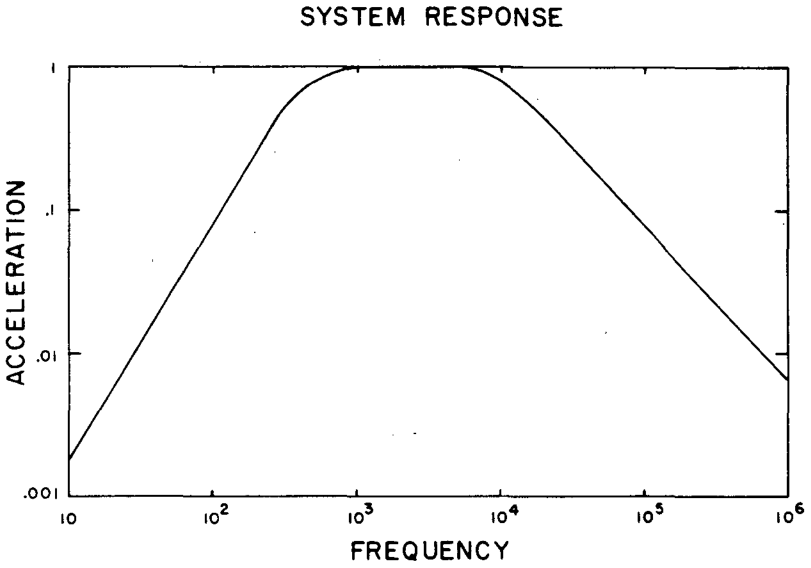

Figure 3. Frequency response of system.

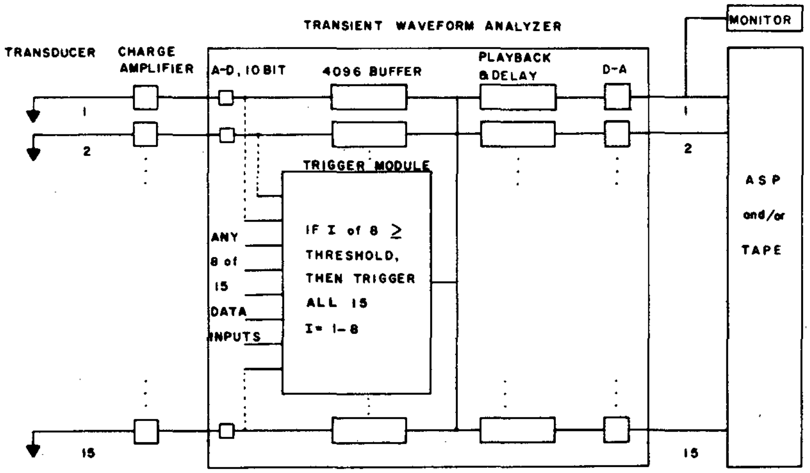

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Figure 4. Block diagram of AE system.

After consideration had been given to the frequency content of the background noise, the attenuation properties of the granite, and source dimensions of the expected cracking, it was decided to concentrate on the 1kHz to 10kHz frequency range. These frequencies correspond to source radii of the order of several cm, using Brune's static model. Although much higher frequencies will be generated by smaller fractures, they would be undetected in the 50 m x 20 m x 10 m array employed in this experiment. The lower frequency was selected on the basis that sources larger than several meters in dimension would probably be too infrequent at the stress levels encountered at 420 m subsurface. In addition, at frequencies less than 1kHz, cultural noises are a problem.

The accelerometers are mounted in 40 mm diameter stainless steel stock, as illustrated in Figure 5. These assemblies were epoxy-cemented into the 48 mm diameter drill holes shown in Figures 1 and 2. Those numbered AE1, 2, 3, 8, 9, 10, 11, 12, 17, 18, and 19 are shallow, horizontal holes 0.3 to 0.6 m above the mine floor. Those numbered AE4, 5, 6, 7, 13, 14, 15, and 16 are inclined holes 6.5 m to 7 m deep, drilled from the side drifts such that they bottom midway between the center and side drifts at a level even with the bottoms of the canisters. The deep holes numbered AE5, 6, 14, and 15 contain accelerometers. The one numbered AE13 contains a piezoelectric source for velocity and attenuation monitoring. In total, 15 accelerometers are installed to form a three-dimensional array centered on the row of canisters.

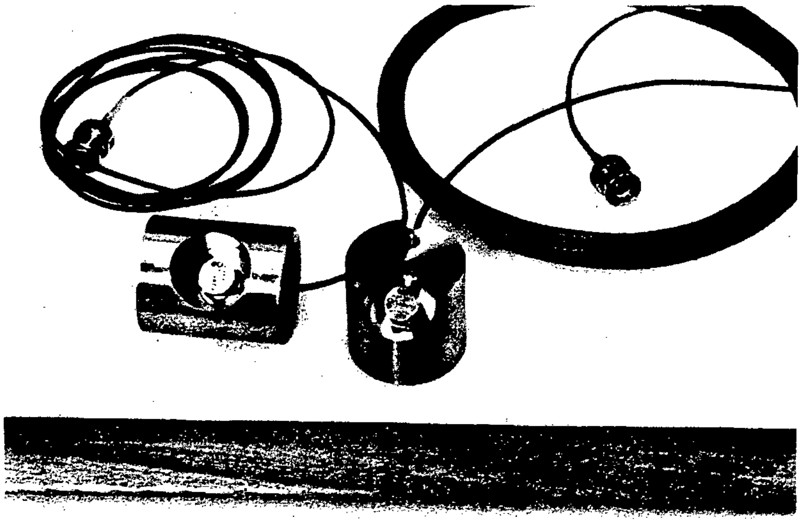

Figure 5. Accelerometers in stainless steel housings.

The amplified signals from the sensors are sent to the instrument alcove and digitized to 10bit accuracy at 100,000 samples/sec by the transient waveform analyser. If the signal level rises above a preset threshold, a 4096-point data window is captured by the waveform analyzer and played back at 20 samples/sec to a slow-speed 14-channel tape recorder (frequency response DC to 40Hz) or to the automated seismic processor at 400 samples/sec. A triggering module monitors 8 of the 15 stations. If any 1 to 8 (selectable) of these 8 stations' signals rise above a preset threshold, that event triggers the playback for the 4096-point data window on all 15 channels at the reduced rate. Between events the raw data are sent real-time to the recorder and ASP. A visual monitor on one of the trigger stations provides a continuous record of events so that they can easily be located on the magnetic tapes. Except for the transient waveform analyzer, the system is identical to that used to monitor and record earthquakes. The waveform analyzer permits the scale-down from high AE frequencies to the much lower earthquake frequencies.

If a large number of events occurs, full processing of the data is tedious, time-consuming and far more labor-intensive than is desired. A similar problem was encountered in applying passive seismic techniques to geothermal exploration [Majer and McEvilly, 1979]. For that study, to process fully a data set of 100 events recorded at 12 stations required several months work. As a result, an in-field processing and virtual real-time display of seismic event source parameters was designed and fabricated. This Automated Seismic Processor (ASP) is microprocessor-based, parallel-processing computer. It is self-contained, low-power (CMOS, 1 watt/channel), capable of providing sophisticated data analysis, and thus elimnates the need for peripheral data storage devices or computers. Basically, a set of real-time algorithms perform event detection, P- and S-wave timing and amplitude functions, then Fourier transforms are calculated and processed to determine source parameters for the events. The present modes of calculation are:

(1) Event count, number of events from turn-on which have met amplitude and occurrence criteria.

(2) Event location, (x,y,z,t), residuals.

(3) b-values, cumulative and interval, for P- and S-wave amplitudes (maximum likelihood method).

(4) Source properties from spectral data; i.e., using D.C. level, corner frequency, and high frequency slope, to estimate the moment, source area, displacent, and stress drop.

(5) First motion polarity for fault plane solution.

(6) Debug mode, all raw data are printed out.

A more detailed description of the ASP can be found in McEvilly and Majer (1982).

RESULTS

Continuous monitoring of AE activity in the Climax stock began on January 11, 1980. Several experiments were carried out to obtain a velocity model necessary for event location. Using a sledge hammer and a piezoelectric source at known distances from the sensors, we determined the velocities of P- and S-waves to be approximately 5.5 to 5.9 and 3.2 to 3.6 km/sec, respectively, for a Poisson's ratio of 0.20 to 0.25, a value consistent with the 0.21 measured by static methods on core samples. The in situ value is averaged over a larger distance, including any alteration, jointing, and fracturing effects which tend to reduce the shear modulus of the rock mass, whereas the laboratory value was measured on intact samples. Paulsson and King (1980) found similar values using cross-hole velocity methods for Stripa granite in Sweden. The accuracy of our velocity model for event location was tested by striking the rock at known sites and using the arrival times to locate the event. For sources near the mine floor, the accuracy of the locations appears to be about ± 1 m. For sources outside of the array the travel paths are obscured by the drifts, and the location accuracy decreases significantly. Our interest lies, however, mainly in events induced by the heaters and canisters, which are all within the array. Our precision is a function of sample interval (10μ sec) and P-wave velocity. Assuming a point source, our basic distance uncertainty is 5.5×10^5 cm/sec $\times 10^{-5}$ sec = 5.5 cm. However, deviations from the homogeneous whole-space assumption in rock properties introduces the observed errors in the locations. We expect to achieve an accuracy of a few tens of cm by using repeated calibration sources and station corrections with the assumption that the velocity model is both time- and space-dependent.

Shown in Figure 6 is the rate of acoustic emission activity through October, 1981. As can be seen there was a background level of activity prior to waste emplacement of 2-3 events per week. The first recorded natural event shown in Figure 7 occurred approximately six days after monitoring began, before any heaters or canisters were installed. The event was located in the north pillar near AE 2, where a convergence-monitoring hole had just been completed. At this time, the preamplifier gains were 20 dB. After several weeks, the gains were increased to the present setting of 40 dB, resulting in an increase of detected events from one per week to two or three per week. Several features of the event in Figure 7 are note-worthy. First is the signal character: it has an impulsive beginning, P- and S-waves are generated, and the first motion of the P-waves varies with azimuth. Were the scale in seconds, rather than milliseconds, Figure 7 could be an average microearthquake as might be recorded over a seismograph network with dimensions of 10-20 km. These facts imply that for at least this event, the source theories developed for earthquakes can be applied on this scale. Assuming scaling laws apply to earthquake source parameters, the source radius of this fracture is of the order of several centimeters. Depending on the location and rate of occurrence of such events, significant fracture permeability may be introduced at least locally by such microseismic activity.

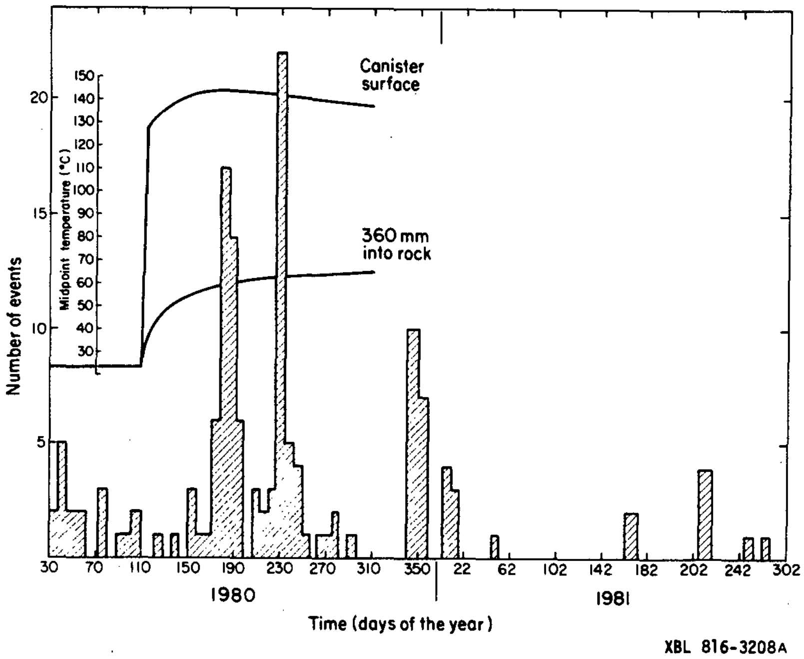

Figure 6. AE activity and temperatures during 1980 and 1981.

In Figures 1 and 2 are shown a group of events located prior to waste emplacement and heater turn-on. The events seem to be located near expected stress concentrations at the corners of the mined openings and near large drill holes. There were no events located near the future location of the waste canisters or heaters. Just prior to waste emplacement there was a period of relatively low human activity within the mine. During this time, the number of events subsided to about one per week, implying that much of the seismicity may represent stress relief caused by construction activity, such as drilling or coring. After emplacement, the activity dropped significantly. When no events were recorded during the first two weeks, it was decided to change the stations used for triggering. Previously, AE2, 14, and 15 were selected as the three stations which must receive a signal greater than 1/16 full-scale (approximately 0.03 g) within a 20 msec window in order to define an event. When the trigger stations were changed to the pair AE14 and 5, activity was detected at the rate of one or two events per week near the canisters.

Since waste emplacement in April, 1981, there have been 3 peaks in activity. The first peak in activity corresponded to "swarm" type of events. These events occurred at rates up to 10-15 per hour, but only once or twice per week. They are characterized by their emergent onsets, as illustrated in Figure 8. These swarm type of events are also all equal in magnitude, implying stress distribution and material properties under normal rock-type behavior. These swarm events were located at shallow depths near the mine floor near canisters 11 to 15, possibly in the concrete. Later visual inspection revealed cracking in the concrete around the top of the canister holes. These cracks appeared to be the result of compressive stresses due to the expansion of the steel liners in the canister holes.

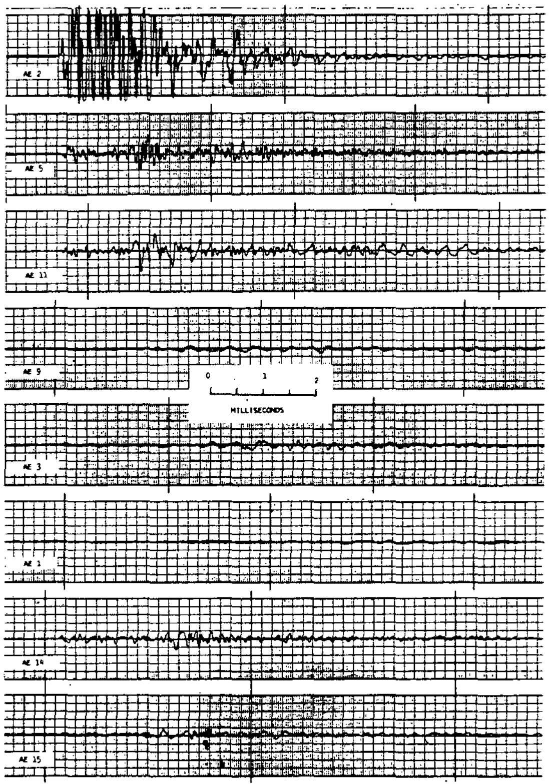

Figure 7. AE event No. 1 (near AE2).

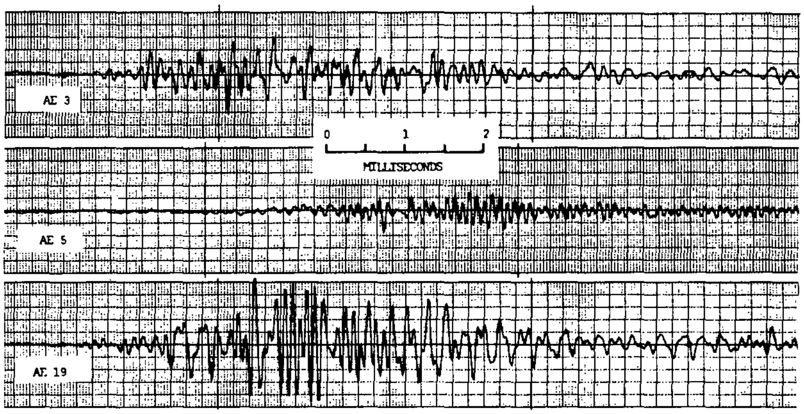

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Figure 8. Example of "swarm" type of AE event.

The second peak in activity occurred several months after emplacement. Unlike previous activity, these acoustic emissions were located beneath the mine floor between the canisters. These events were more like the "normal" rock fracturing events. They had impulsive beginnings and were distributed in space and time as would be expected of microearthquake activity. To date, they are the only events that may be associated with the rock heating.

The last major peak in activity occurred in December, 1980. These events were located in the north pillar between AE2 and AE11, near mapped fracture zones. They appear to be the result of natural stress release, although it does seem unusual no other large sequence of events such as these had occurred before. Although possible, it is doubtful that these events are in response to the overall thermal loading of the repository region, especially considering the small rise in temperature several meters away from the heat sources.

Since the last peak in activity there have been surprisingly few events. This lack of activity may be due to the fact that the temperature is decreasing near the canisters, or that what stress readjustment was necessary, has already occurred. The maximum rock temperature for this simulation of waste storage was only 65-70°C at a distance of 360 mm into the rock. Most laboratory experiments indicate that at least for granite, acoustic emission activity does not begin until approximately 70°C. Assuming that these temperatures are representative of a full scale repository, it appears that from the standpoint of induced fracturing due to thermal loading, granite is a safe medium. However, only further monitoring will definitely reveal the overall response of the thermal loading of this region due to storage of nuclear waste.

During the initial monitoring period, the firing of several nuclear test explosions at NTS provided an opportunity to study the potential for induced fracturing within the repository due to strong ground shaking. The ground acceleration estimated within the repository, associated with an underground test some 10 km distant, is approximately 0.05 g. This would be considered as strong motion in an earthquake context. There were, however, no AE events detected that were associated with the ground motion from these explosions. This observation includes one shot occurring after waste emplacement and heater turn-on. Implications are that the repository integrity may be maintained in the presence of fairly strong ground motion from nearby sources.

The apparent attenuation characteristics of the P-waves' first cycle for different paths are also interesting. Referring to Figures 1, 2, and 7, it can be seen that the amplitudes are not the same for stations AE14 and AE15, equidistant from the source. In general, it appears that amplitudes at AE15, 9, and 1 are reduced compared to those at AE14, 11, and 3. A mapped fracture zone cuts across the mine and separates these six stations. The stations with the larger amplitudes were on the same side of the fracture zone as the source. It is also interesting that most of the detected seismic events recorded to date have occurred roughly along this zone, although this may reflect that the network has been set with maximum response in this central zone.

Since late October, 1980, the wave propagation characteristics (travel time and amplitude) of the P- and S-waves have been monitored daily. These waves are created by a piezoelectric source set in the bottom of the water-filled hole AE 13. As can be seen from Figure 9, there has been little change in the P- or S-wave velocities through the canister area (10 μsec accuracy in 2.8 ms travel time) during the monitoring period. However, the S-wave amplitude relative to the P-wave amplitude has increased significantly for travel paths through the heated zone, as shown in Figure 10. The cause is not known, but may be due to: (1) a change in water content in the heated zone; or (2) a change in the shear and bulk modulus of the rock matrix due to thermal expansion. There have been fluctuations in the P-wave amplitudes relative to a reference station (AE19), but these changes have not been systematic and vary only by a factor of two. All amplitudes were measured peak-to-peak on the first cycle only.

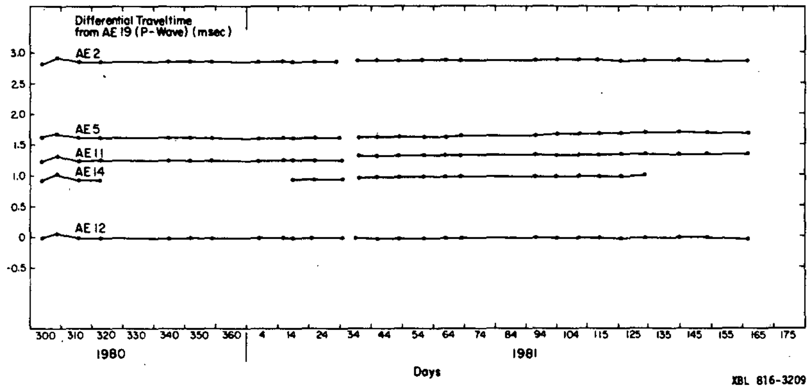

Figure 9. Travel time differential, referred to AE19, from transmitter in AE13.

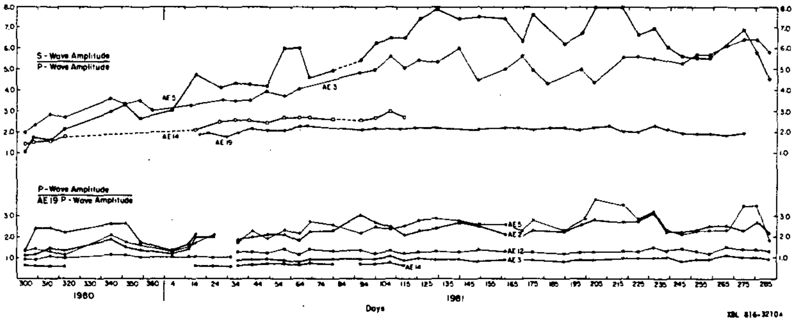

Figure 10. P- and S-wave amplitude changes, referred to AE19, as a function of time.

SUMMARY AND CONCLUSIONS

An experiment has been designed and deployed to characterize acoustic emission and microearthquake activity related to thermal, radiation, and mining effects at a simulated underground nuclear waste repository. The development of high-speed microprocessors has made it possible to develop an automated seismic processor to monitor and to analyze data in-field under conditions close to real-time, applying techniques used in the fields of acoustic emission and earthquake seismology. The experiment has been designed to detect and analyze the occurrence of fractures with length dimensions from a few centimeters to a few meters. Preliminary findings are:

(1) The repository rock has average P- and S-wave velocities of 5.5 to 5.9 and 3.2 to 3.6 km/sec, respectively, for a Poisson's ratio of 0.20 to 0.25.

(2) The rock mass on this scale is not homogeneous in velocity and attenuation properties of seismic waves at frequencies between 1 kHz and 10 kHz. Ongoing observations of these properties may offer a means of mapping the progress of fracture zones or zones of alteration.

(3) There are discrete seismic events occurring within the mine structure, not associated with the canister area. These events seem to occur at a rate from 1-3 per week as discrete fractures with source dimensions of the order of centimeters, doubtless in response to stresses induced by mining, drilling, and coring.

(4) After waste emplacement and heater turn-on, discrete seismic events were detected in the previously quiet canister drift, both in the concrete and rock surrounding the canisters. The spectral characteristics of the seismic waves resulting from these events indicate source dimensions of the discrete fractures to be of the order of several centimeters. The mechanism governing the failure process has not yet been established.

(6) Changes in P- to S-wave amplitudes indicate a possible drying out of the canister region.

These results are encouraging and confirm the experimental concept. The automated seismic processor should provide the desired monitoring and analysis sophistication necessary to characterize the AE response of the repository rock to the imposed thermal and radiation sources. The experiment will now address questions relating to ongoing physical processes within the mine through observation of their effects on acoustic emission and microearthquake activity.

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