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Ernest L. Majer, Thomas V. McEvilly, and
Michael S. King

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Ernest L. Majer
Lawrence Berkeley Laboratory

Thomas V. McEvilly
Seismographic Station
Department of Geology and Geophysics

Michael S. King*
Department of Materials Science and Mineral Engineering

University of California
Berkeley, California
94720

ABSTRACT

An experiment utilizing microearthquake and acoustic emission techniques has been designed to investigate the discrete failure and behavior of hard rock in response to storage of high level nuclear waste. Data are presently being collected from a fifteen-station, three-dimensional array of piezoelectric sensors surrounding eleven canisters of spent nuclear fuel and six electrically heated simulator canisters. The canisters are arranged in a linear array 420 meters beneath the surface in the Climax Stock at the Nevada Test Site. Because of the unique scale of the experiment (array dimension - 50 m x 20 m x 10 m), techniques employed are drawn from the fields of acoustic emission and earthquake analysis. The data are digitized and analyzed in-field via an Automated Seismic Processor (ASP) developed for microearthquake studies. Although the discrete events are high frequency in nature (1 khz to 10 khz) their behavior and appearance are typical of shear failure observed in microearthquake sequences. Sought are not only the spatial and temporal characteristics of the events with respect to induced thermal, mechanical, or radiation stresses, but also a complete understanding of the source characteristics relative to these induced stressses. The velocity and attenuation characteristics within the array imply that the rock is not homogenous to acoustic waves at the observed frequencies. This paper reviews the basis for the experiment's concept, the instrumentation emplaced, and preliminary results of the monitoring program.

*On leave from the Department of Geological Sciences, University of Saskatchewan, Saskatoon, Canada.

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INTRODUCTION

The suitable isolation of waste radioactive by-products has become a crucial issue in the future development of nuclear-powered electric generating plants. A proposed solution to this problem currently under study is storage in underground repositories. An important and incompletely known aspect of underground storage is the interaction between the nuclear waste and the host rock. Among the many factors to be considered in this interaction are the response of the rock to changes in stress due to the mining of drifts or to thermal loading from the waste, the effects of radiation, the influence of storage drift backfilling, and the role of potential subsequent subsidence above the repository. Significant stress or strength changes in the host rock may induce fracturing, thus enhancing rock permeability which in turn would increase the accessibility of the waste to ground water, with the potential danger in the release of toxic substances into the biosphere. Also of concern are unknown preexisting fractures either induced from mining or naturally occurring, but not detected by drill holes or evident in the underground workings. All of these factors represent potential serious problems in assuring the long term stability and integrity of a repository.

Full-scale experiments conducted underground in realistic openings are required to investigate the relative importance and interaction of the various effects tending to compromise the repository integrity. Such experiments, incorporating different design geometries, temperatures, and radiation levels, must be carried out in media representative in composition, permeability, and confining pressure to planned in-situ repository conditions. Measurements must be made at sensitivities that permit detection of what may be very long-term processes.

A potential monitoring method, with the natural advantage of concentrating these expected long-term effects into less frequent but much larger transient events, is based on the observation of acoustic emission (AE) or microearthquake (ME) phenomena. Differing only in 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 exist [Johnson, 1979] in microearthquake seismology for locating and describing the nature of such sources of elastic wave radiation, and these methods should be applicable with proper scaling to the investigation of AE events in a stressed underground repository. This study investigates the applicability of both microearthquake and acoustic emission techniques in monitoring the integrity of an underground waste respository. Questions addressed relate to the scaling laws of earthquakes and source mechanisms and the nature of thermally-induced fractures.

There have been few studies of seismic activity carried out on this scale. In one such experiment at Stripa, Sweden, conducted by the University of California, Lawrence Berkeley Laboratory (LBL) and the Swedish KBS, electric heaters in granite were used for the study of thermal stress effects. Acoustic emission studies were started well after heater turn-on, and only one sensor was used. However, considerable activity was observed associated with the heating phase, and activity increased during the cool-down period [R. Rachiele, 1980, personal communication].

Other workers have studied AE activity as a function of temperature in the laboratory. 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 Wong [1980] investigated AE generation at atmospheric pressure and over the temperature range of 20°C to 120°C that the AE rate increased abruptly in Westerly granite at a threshold temperature of 70°C. They also found that above the 70°C threshold the total number of acoustic emissions depends on the rate of heating, as well as the maximum temperature; i.e., the faster the heating, the more events per unit time. In a dry sample, the rate of AE was much higher than that for a water-saturated sample at equal temperature and heating rate. They attributed this to differences in thermal gradients between a dry and water-saturated sample; i.e., in a saturated sample, the thermal gradients within the rock are smaller than in a dry sample. It is not known what mechanisms will dominate in a scaled-up version of these heating processes. Differential thermal expansion will undoubtedly be important; however, the scale on which it will occur is unknown. Finally, the effect of uneven cooling due to partial water saturation of inhomogeneous material and unusual geometry may also play an important role in the fracture mechanism.

THE CLIMAX REPOSITORY EXPERIMENT

Another full-scale experiment, the spent fuel test being carried out by the University of California, Lawrence Livermore National Laboratory (LLNL), in the Climax stock at the Nevada Test Site (NTS), offers a unique opportunity to investigate many of the problems associated with the storage of nuclear waste, and to evaluate the utility of AE measurements in defining failure details. The general objective of the Climax experiment is to test the feasibility of short-term storage of spent fuel assemblies from commercial reactors at a reasonable depth in a crystalline igneous rock, followed by retrieval of the assemblies. Only a summary of the project will be given here. For a more detailed description, the reader is referred to Ramspott *et al.*, [1979].

Figure 1 is a layout of the experimental facility, 420 meters beneath the surface, showing the location of the spent fuel assemblies and heaters.

The center drift is the storage area for a linear array of eleven spent fuel assemblies and six heaters. The waste canisters and heaters are located in steel-lined vertical holes on three-meter centers. The experiment provides simulation within a 15 m by 15 m area of the first five years of operation of a repository. Electrical heaters are included to study the effects of heat along versus heat plus radiation. The thermal output of the waste canisters and heaters in the center drift will be 2 kw (2.5 year-old spent fuel assemblies). The surface radiation of the spent fuel assemblies is 1.3×10^8 mrem/hr (1.3×10^8 mrem/hr, gamma; 1.6×10^3 mrem/hr, neutron). The two side drifts each contain 10 smaller heaters on six-meter centers. These heaters will be used to produce a temperature field in the canister drift and adjacent pillars which will simulate the conditions in a large repository. The maximum temperature in the rock is expected to be 100^oC, ten months after emplacement. Rock temperature, stresses, and displacement will be monitored continuously with 430 thermocouples, 18 (vibrating wire) stress meters , 116 extensometers, and 34 convergence heads.

The Climax Stock is composite granodiorite and quartz monzonite. It is an intrusive body bounded on the east and west by faults, with a surface exposure area of 4 km^2 and widening to an estimated maximum extent of 100 km^2 at several kilometers depth [Maldonado, 1977]. Some relevant properties of the Climax quartz monzonite are: dry density 2.60 - 2.66 g/cc, porosity 0.7 - 1.1%, compressive strength 210 MPa, Youngs Modulus 61.4 - 69.7 GPa, Poisson's Ratio .21 -.22, and thermal conductivity 3.0 w/m^oK [Ramspott et al., 1979].

The Climax Stock was the site of two nuclear explosions, HARDHAT 5 kt, 1962, and PILEDRIVER 61 kt, 1966, centered approximately 210 and 460 meters, respectively, from the canister drift. It has been determined by Borg [1970, 1972] that the zone of associated microfracturing did not extend to the present experiment area.

The location of the permanent water table is not yet defined precisely at the Climax Stock because of the very low permeability of the granite. At the 420-meter level, the rock seems to be unsaturated but not dry. Several seeps are seen throughout the workings, but the majority of holes drilled for the AE sensors are still dry, even after six months. This behavior is not usual of that observed below the "water table" in very tight rock masses.

SEISMOLOGICAL METHODS APPLICABLE TO REPOSITORY MONITORING

An experiment has been designed to monitor AE and ME activity and wave propagation effects within the Climax test area as an added study of repository stability relative to thermal and mining effects. Any mechanical effect of radiation, i.e. degradation or weakening, will probably be confined to the first several cm of rock and therefore probably minimal. Ideally, it would be desirable to study the operative fracture formation process from microscopic to macroscopic scale. Practical considerations of equipment sensitivity and dynamic range limits the experimental scale of fracture studies. The Climax Stock project provides a unique opportunity to study in detail the fracture process on a scale between the laboratory (AE) and normal field observations (ME). Methods developed in microearthquake and acoustic emission analyses can be applied at the scale of tens of meters in the spent fuel test area.

In the last 15 years seismologists have given considerable attention to detailed seismic source descriptions [Johnson, 1979]. The literature addresses both static and dynamic source characterization. Of the static descriptions, the semi-empirical approach of Brune [1970, 1971] is the most widely applied. This method estimates three independent source parameters from the spectrum of either the P- or S-wave. 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 thus imply different stress drops. Recently, spectral analysis methods have been applied to the field of acoustic emissions [Pollack, 1980]. Efforts to date have been toward defining different AE source processes from the frequency content of the signals. Jax [1974] found that even for sources with frequency content as high as 500 kHz there was a correlation between material properties (in this case, grain size) and source duration. Other workers [Wolitz et al., 1978] have been able to categorize types of failure in fiberglass from spectral content. Spectral data have also been useful in discriminating signals from noise, and in studies of plastic versus brittle deformation [Pollack, 1980].

Other techniques used in earthquake studies include the fault plane solution [Byerly, 1926] and "b-value" determination. AE studies have generally ignored the fault plane approach to determine the principal stress direction and geometry of the fracture plane. However, AE researchers have used b-value studies (Log N = a - bM, N = cumulative number of events, M = magnitude of events) to infer particle size and ductility of materials [Pollack, 1980]. On the other hand, earthquake studies using the b-value to characterize the mode of faulure have generally concluded that the b-value seems to vary with the distribution of the applied stress field and with the homogeneity of the material [Mogi, 1962; Scholz, 1968; and Wyss, 1973].

In our experimental case of monitoring AE/ME for 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 varying stress field. Thermal effects will superimpose an additional stress field, such as the effects of cool water seeping into warmer areas.

Radiation degradation and medium inhomogeneity will add yet another factor influencing failure rates and mechanisms. The Climax seismic experiment is designed to separate these factors, if possible, and to estimate their relative significance.

The seismic data results will be correlated 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 (i.e., thermal, mine geometry, and known fracture zones) will bear on future repository design relative to the density and configuration of canister holes and mine openings. By analyzing the rate and manner of energy release (i.e., b-values, source dimensions, principal stress directions, stress drop) information on the suitability of granite as a repository material will be evaluated. Also of importance is the applicability of the experiment itself. Can the above questions be adequately answered using the techniques described? If not, can the experiment be restructured to do so?

In addition to the above questions, there is the problem of overall mine stability and safety. There has been limited success in predicting failure using AE in metals and alloys [Pollack, 1978]. Considerable effort has been directed toward predicting rock bursts and roof falls in mines, however, with better results [Blake et al., 1974, Brady, 1978]. Common methods applied in AE/ME studies involve monitoring the variations in source locations, number of events, amplitude of events, time between events, event duration, energy release, and spectral content. By far the most generally used of these techniques has been event location and counting methods [Hardy and Leighton, 1980]. This is mainly because the available equipment is not capable of fast on-line processing required for real-time sophisticated analyses. The principal aim of this study will be to characterize the AE/ME activity in more complete terms relative to the on-going physical processes, using ME methods scaled to the Climax experiment.

THE CLIMAX SEISMIC EXPERIMENT

The equipment selected to monitor the AE/ME activity includes Columbia 5002 piezoelectric accelerometers, Columbia 9021 charge amplifiers (40 dB gain) and a 15-channel Physical Data 515-A 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 shown in Figure 2a and 2b, respectively.

Considering 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 1 kHz to 10 kHz frequency range. Using a static model (Brune's) these frequencies correspond to source radii on the order of several centimeters. Although much higher frequencies will be generated by smaller fractures, it was felt that to adhere to the objective of examining the overall stability of the repository, sources much smaller than a few centimerers would not be significant, nor would the higher frequencies be detectable using an array the size of the subject experiment. The lower frequency range was selected on the basis that sources larger than those emmitting dominant frequencies less than 1 kHz (i.e., several meters in dimension) would probably be too infrequent at the stress levels encountered at the 420 meter level. The experiment would also be subject to cultural noises such as vehicle movement, construction activities, etc.

The accelerometers were mounted in 40 mm diameter stainless steel stock (Figure 3). These assemblies were then epoxied into 48 mm diameter drill holes. The holes are located as shown in Figure 1 (numbered symbols). AE 1, 2, 3, 8, 9, 10, 11, 12, 17, 18, and 19 are shallow, horizontal holes 0.3 to 0.6 meters above the mine floor; AE 4, 5, 6, 7, 13, 14, 15, and 16 are deeper (6.5 m - 7 m), inclined holes drilled from the side drifts such that the bottoms of these holes are midway between the center and side drifts and at a level even with the bottoms of the canisters. Presently, all shallow "surface" holes contain an accelerometer. Deep holes, AE 5, 6, 14, and 15 contain accelerometers. AE 7, 4, 16 and 13 will be used for emplacement of piezoelectric sources for velocity and attenuation monitoring. In total, 15 sensors are installed to form a 3-dimensional array centered on the canister row. The amplified signals from the sensors are sent to the instrument alcove and digitized to 10-bit accuracy at 100,000 samples/sec by the transient waveform analyzer. 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 D.C to 40 Hz) or to the automated processor at 400 samples/second. 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, then that event triggers the playback for the 4096 data window on all 15 channels at the reduced rate. Between events the raw data are sent real-time to the recorders and processor. Data tapes are now changed every eight days and returned to the laboratory for manual playback and analysis. A visual monitor on one of the trigger stations provides a continuous record of events so that they can be easily located on the magnetic tapes. Except for the transient waveform analyser, the system is identical to that used for monitoring and recording earthquakes. The waveform analyzer allows the scale-down from earthquake work.

If a large number of events occur, the full processing of the data is tedious, time consuming, and far more expensive and labor-intensive than desired. We have encountered a similar problem 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. The result of this experience has been the design and fabrication of an in-field processing and virtual real-time display of seismic event source parameters. This Automated Seismic Processor (ASP) is a microprocessor-based, parallel-processing computer. It is self-contained, low-power (CMOS, 1 watt/channel), capable of providing sophisticated data analysis, eliminating 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 calculate 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, displacement, 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 (1980).

PRELIMINARY RESULTS

Continuous monitoring of AE/ME 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 of about 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 in 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 meter. For sources outside of the array (e.g., on the outer drift walls), the travel paths are obscured by the drifts and the location accuracy decreases significantly. We expected this to occur; however, our interest lies mainly in the 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 x 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.

The first recorded natural event shown in Figure 4 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 4 are noteworthy. 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 4 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 on the order of several centimeters. Depending on the location and rate of occurrence of such events, significant fracture permeablity may be introduced at least locally by such microseismic activity. As more data are obtained, correlations will be made with mapped fractures and faults within the underground openings and with expected stress perturbations from mine openings, heat, and radiation sources.

Figure 5 shows 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 (i.e., drilling, coring, etc.). 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, AE 2, 14, and 15 were selected as the three stations which must receive a signal greater than 1/16 full-scale (i.e., 30 mv, or approximately 0.03 g) within a 20 msec window in order to define an event. When the trigger stations were changed to the pair AE 14 and 5, activity was detected at the rate of one or two events per week near the canisters. After waste emplacement, the detected activity seems to be occurring in two different types of events. The first type is the normal rock fracturing event as shown in Figure 4. These events occur at a rate of one or two events per week and are located in the rock mass. The second type of event is the swarm-type sequence. The swarms (15-20 events per hour) may last only several hours and occur on the average of one per week. These events are not impulsively beginning as are the rock fracture events, but appear quite emergent in character (Figure 4a). The swarm events are also of roughly equal magnitude, whereas the single impulsive events are not. Although more difficult to locate, the swarm type events seem to be occurring in the canister drift at shallow depth near canisters 11-15, possibly in the concrete. Visual identification of cracks in the concrete around the top of the canister and heater holes also occurred several weeks after emplacement. Although the concrete is farther from the heat source than the surrounding rock, the coefficient of thermal expansion for concrete is 2-3 times that of granite [Clark, 1960]. It is not known if the concrete cracked before the rock, if the rock has developed cracks, or if the cracks in the concrete may have already been there and opened when heating began.

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 approximatlely 0.05 g. This would be considered as strong motion in an earthquake context. There were, however, no AE/ME events detected associated with the ground motion from these explosions. This obvservation 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 4 and 5, it can be seen that the amplitudes are not the same for stations AE 14 and AE 15, equidistant from the source. In general, it appears that amplitudes at AE 15, 9, and 1 are reduced compared to those at AE 14, 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.

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 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 after some three months of monitoring prior to waste emplacement and heater turn-on, and several weeks following, 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 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.

(5) There was no evidence that strong ground motion within the respository, associated with nearby underground nuclear explosions, induces cracking or otherwise enhances the microfracturing process.

These preliminary results are encouraging and confirm the experimental concept. The automated processor should provide the desired monitoring and analysis sophistication necessary to characterize the AE/MS 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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TABLE 1

Columbia 5002 Transducer

Sensitivity	13 pcoul/g
Freq. Response	2 Hz to 10 kHz, ± 5%
Resonant Freq.	50 kHz
Capacitance	850 pF
Output Resistance	2×10^{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

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FIGURE CAPTIONS

Figure 1a. Plan view of climax experiment showing waste canisters, heaters, and acoustic emission sensors. Signals from the AE sensor are hardwired to the instrumentation alcove. Power output of the heaters is adjusted to simulate the output of the spent fuel canisters.

Figure 1b. Cross section of mine openings showing AE sensor location in "deep" holes (dashed lines) and "surface" sensors.

Figure 2a. System response (Acoustic Emission sensor mounted on Stainless Steel plus preamplifer). The response was obtained by placing the mounted sensor on a block of granite and pulsing the system with a 1 μ sec pulse to simulate a delta function. The result was then Fourier transformed (source deconvolved) to give the shown results. Although the sampling rate will be only 10 to 5 μ sec, it is felt that the rock will act as a effective anti-alias filter. Units are in Hz and relative accerlation response.

Figure 2b. Total system showing the AE sensor (Transducer), the preamplifiers (mounded as close as possible to the sensor), the transient waveform analyzer (Physical Data 515-A), and the data handling device (either a tape recorder or the Automated Seismic Processor (ASP)).

Figure 3. The Colombia 5002 piezolelectric accelerometer (AE sensor) in their stainless steel mountings. The left configuration is for the horizontal surface holes, the right for the inclined "deep" holes. Both are designed to keep the sensors vertical such that first motion of the P-wave can be used for fault plane solutions.

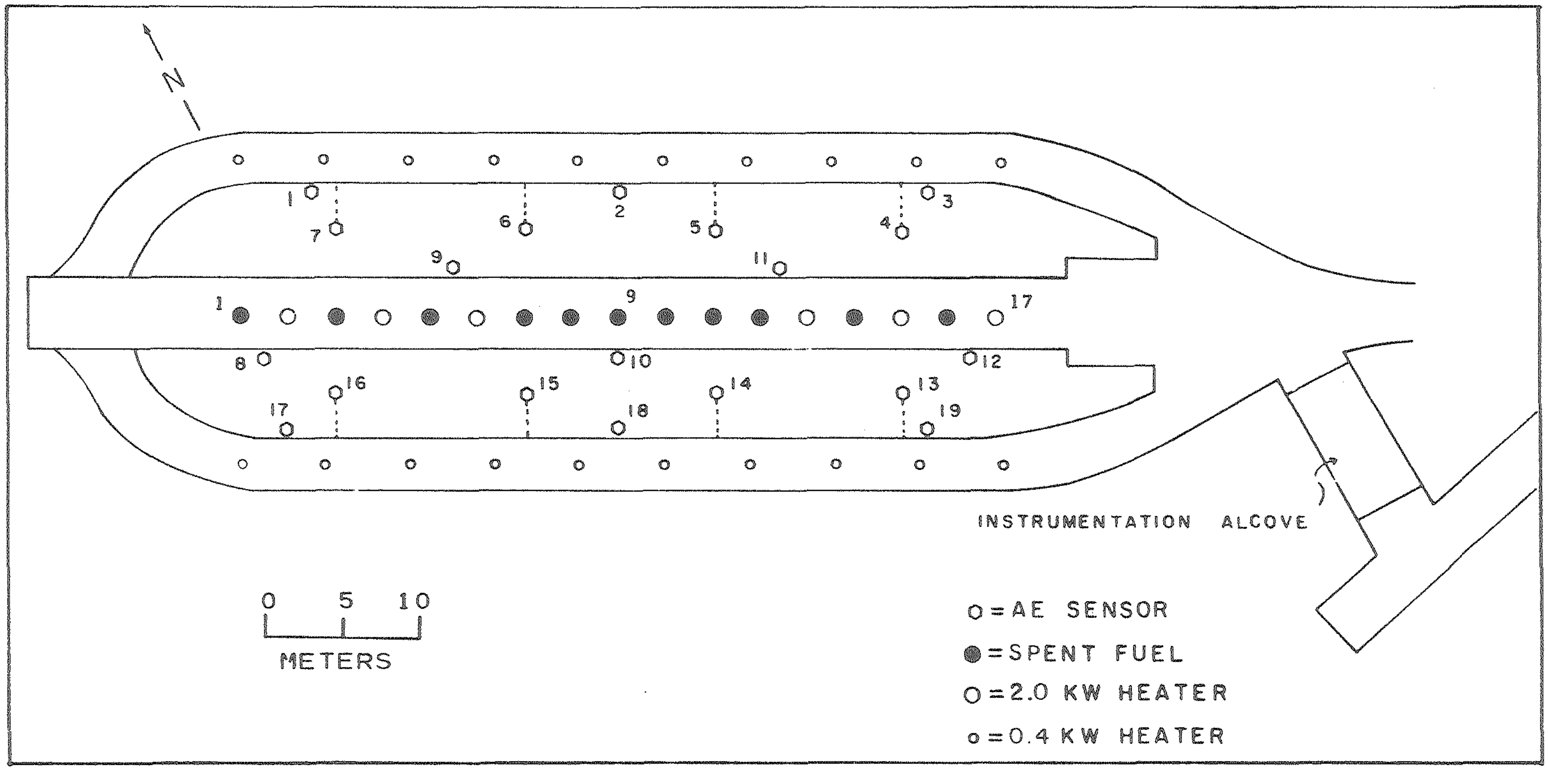
Figure 4. An event from the climax experiment which was located near AE2, i.e., event 1 in Figure 6. Note the character of the event, i.e., impulsive begining, polarity variation with azimuth, and shear wave generation. The amplitudes are all equal gain, however, they have been shifted in time to demonstrate the amplitude differences between stations, i.e., note the the difference between sources equidistant from the source (AE 11 & 9, AE 1 & 3, AE 14 & 15).

Figure 4a An example of the "swarm" type of event. Relative amplitudes and arrival times are correct.

FIGURE CAPTIONS

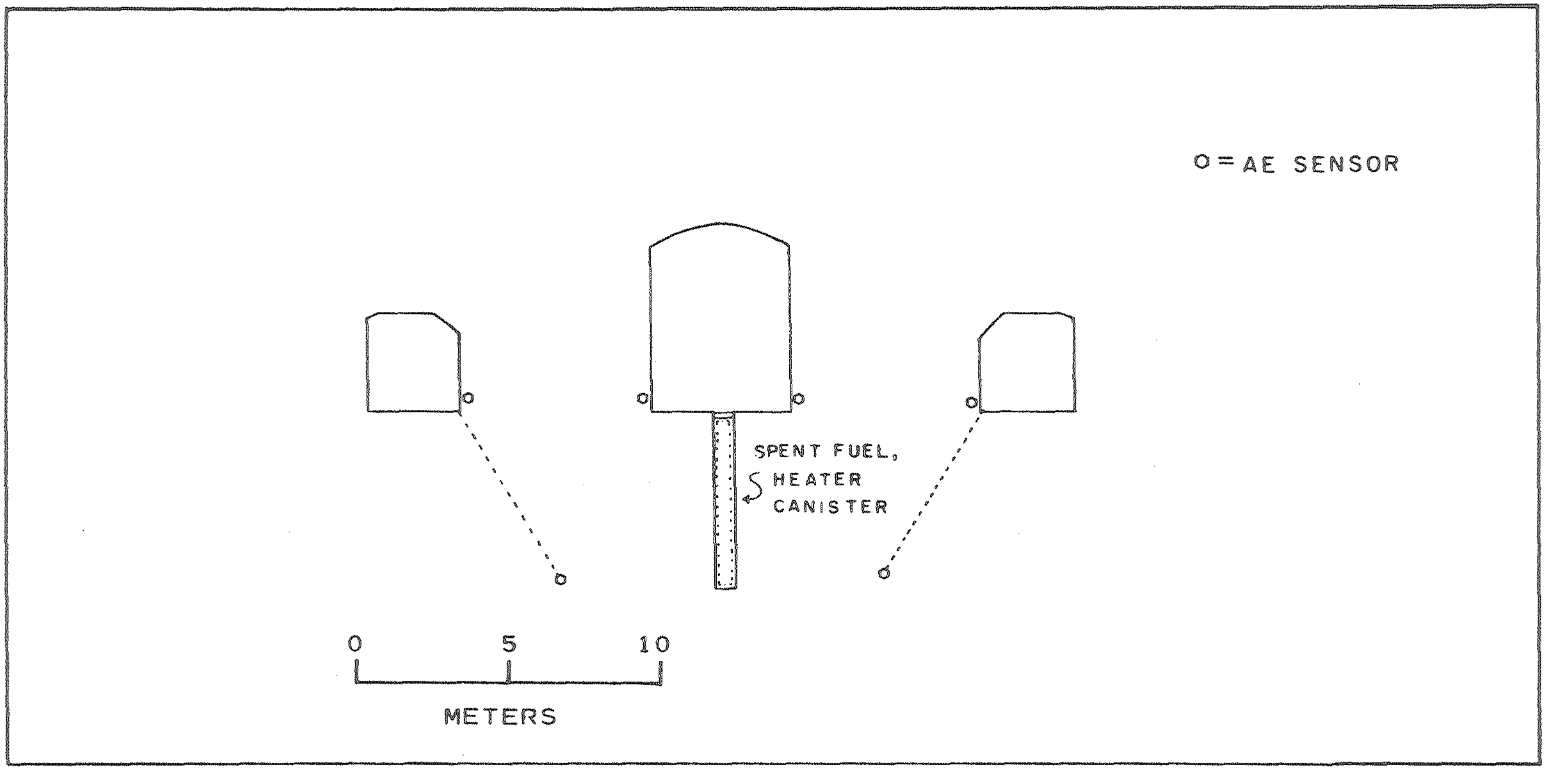
Figure 5a. Plan view of mine showing location of events prior to waste emplacement and heater turn-on. Although the events are clustered in the center near the fracture zone that cuts across the mine, the locations may be due to the trigger scheme used at the time, i.e., stations AE 2, 14, & 15 must have their thresholds exceeded before the remaining stations triggered. However, the present trigger scheme (any I of eight stations, I = 3) has not detected any difference in event location.

Figure 5b. Cross section of mine showing event locations prior to waste emplacement and heater turn-on. Note that no events were located near the canister beneath the mine floor.



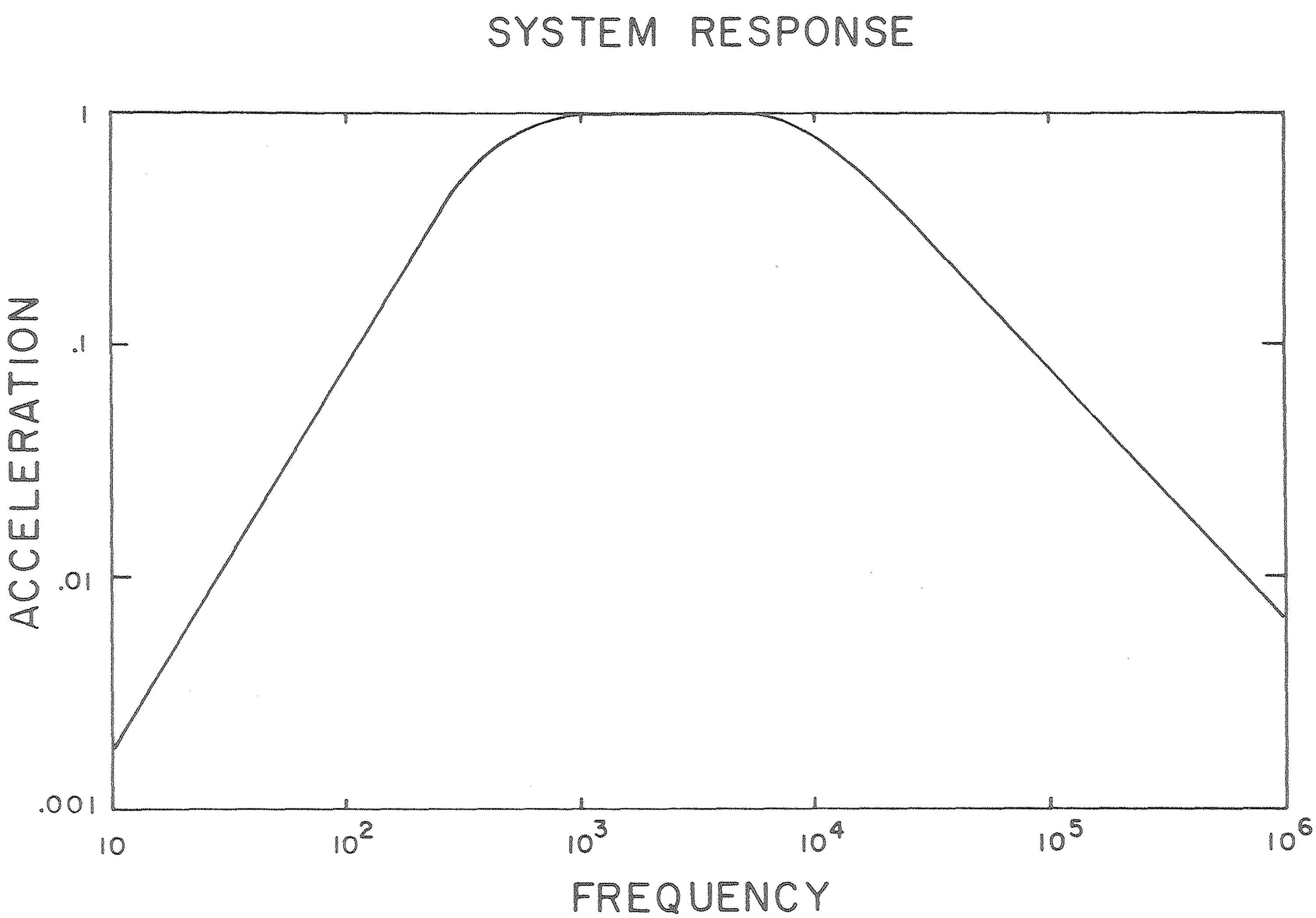
XBL 8010-12309

FIGURE 1a



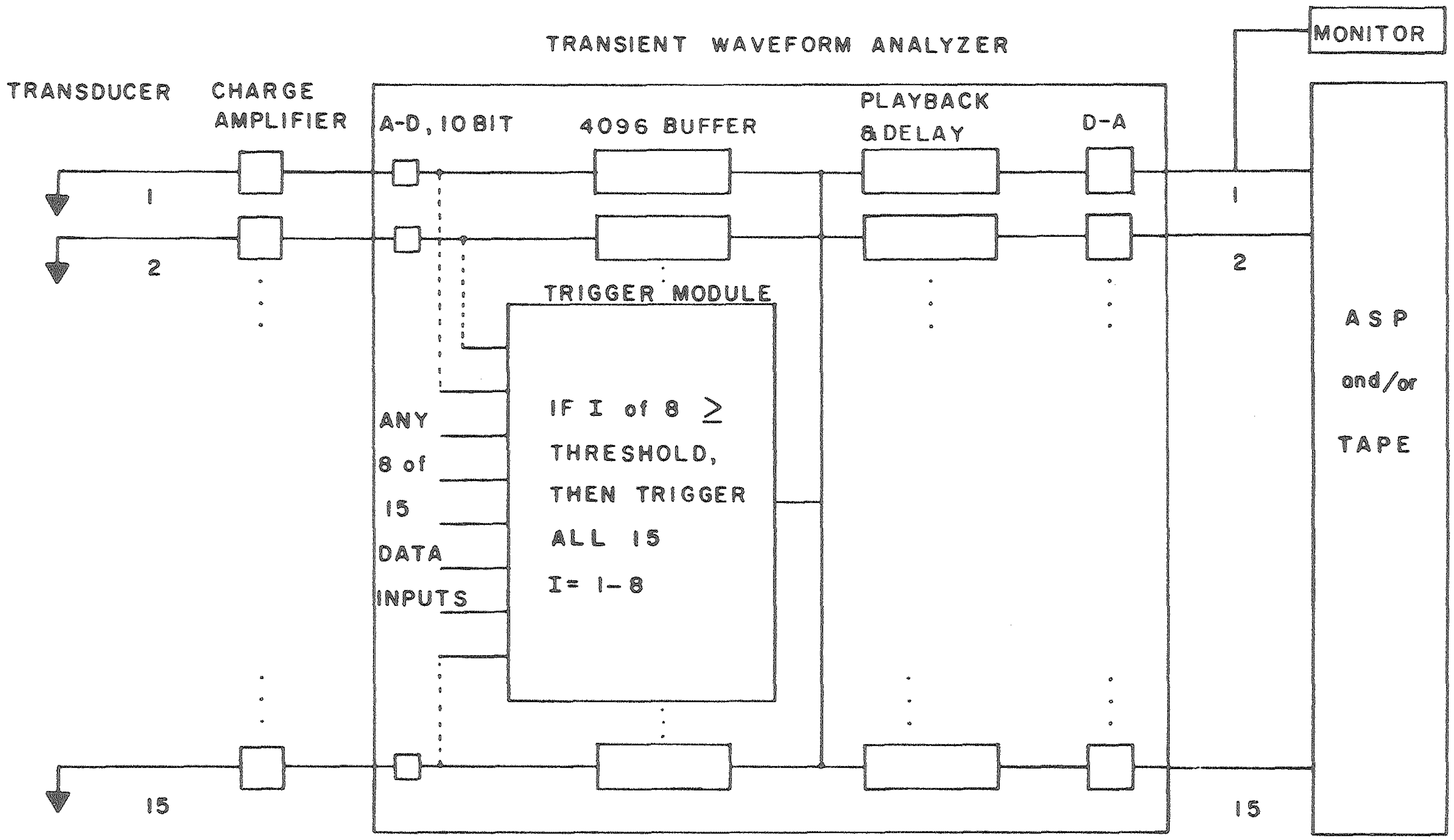
XBL 8010-12310

FIGURE 1b



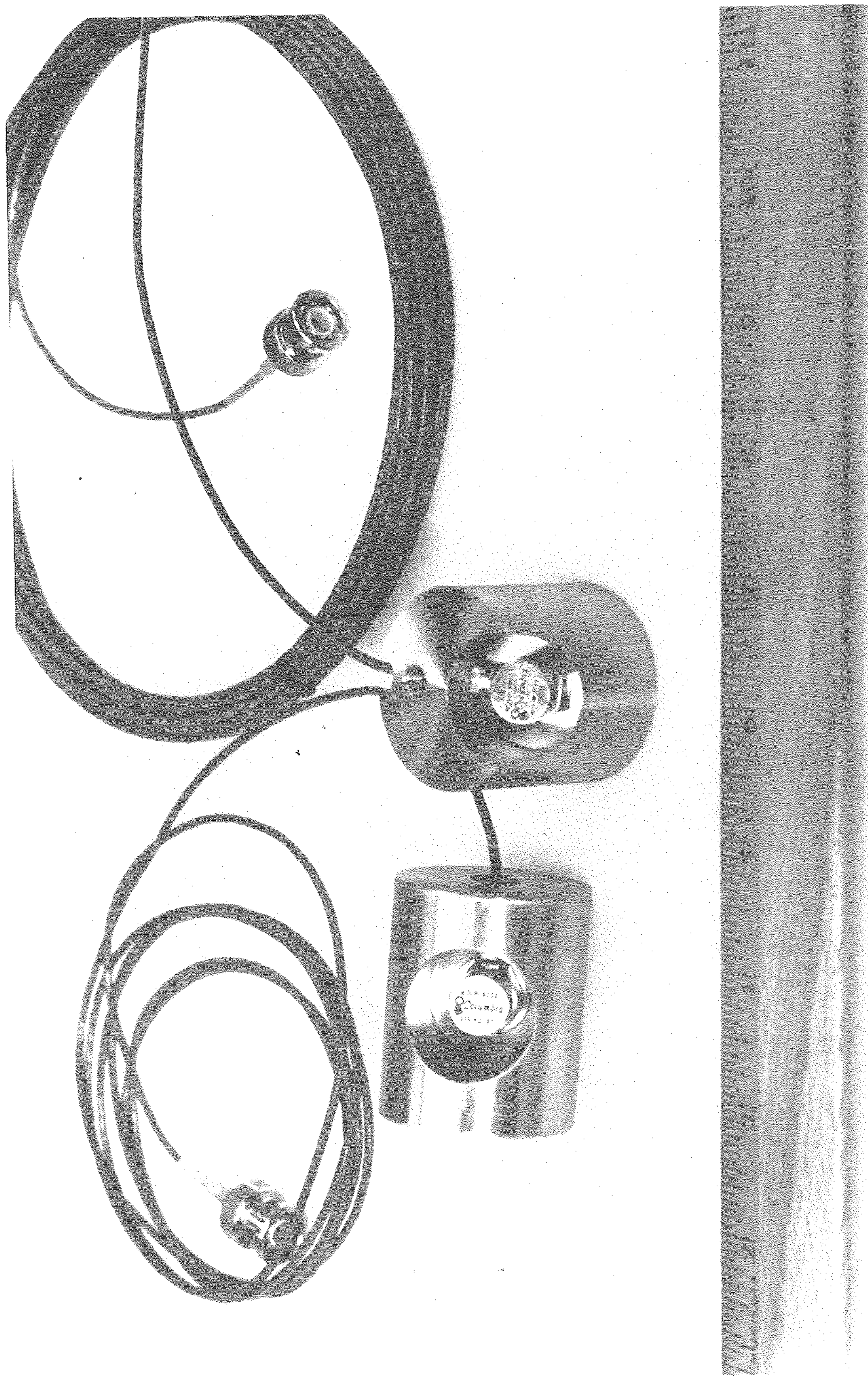
XBL 8010-12308

FIGURE 2a



XBL 8010-12374

FIGURE 2b



XBB 803-2641

Figure 3

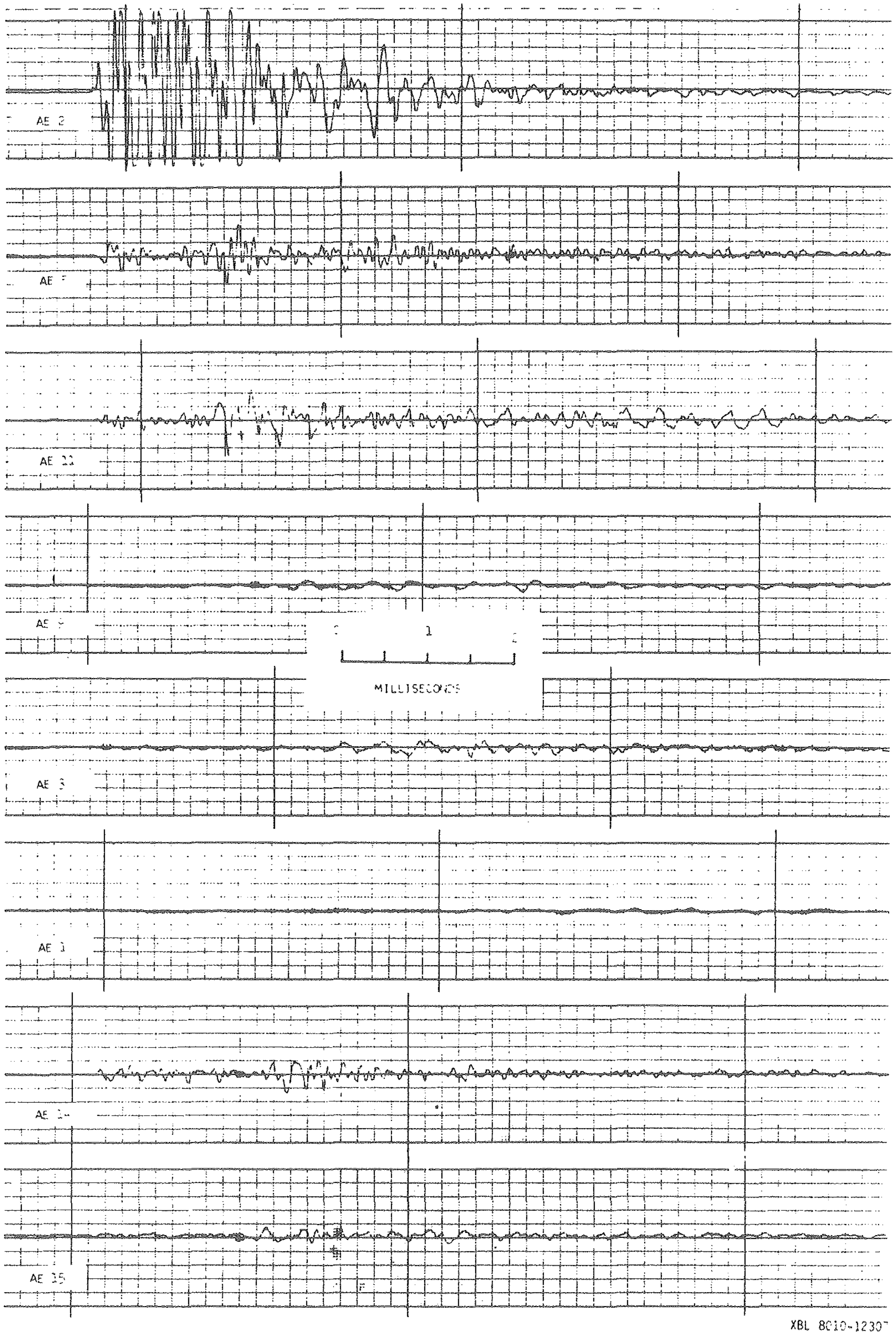

AE 2
AE 7
AE 11
AE 9
0
1
2
MILLISECONDS
AE 3
AE 1
AE 14
AE 15
XBL 8010-12307

FIGURE 4

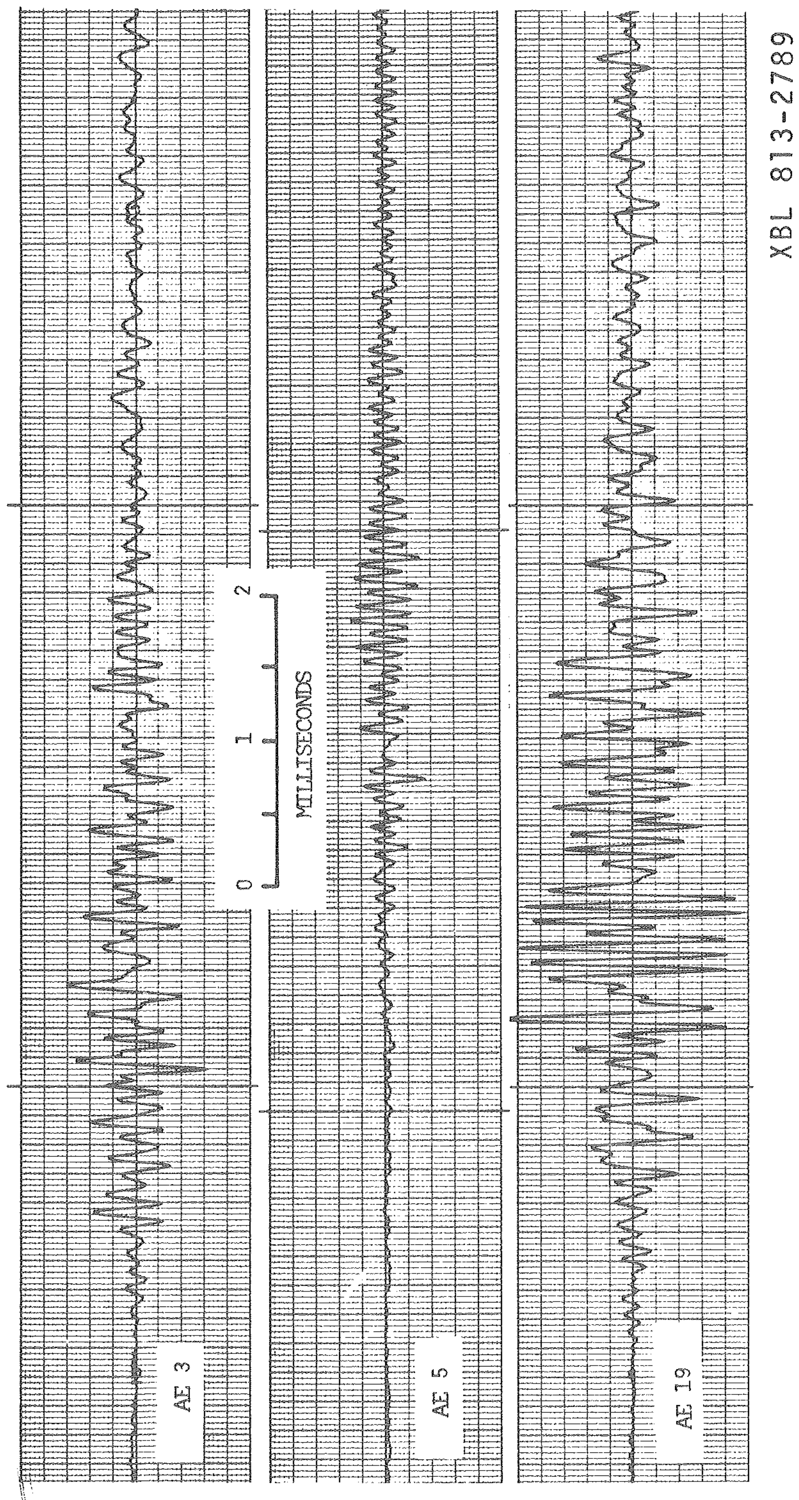
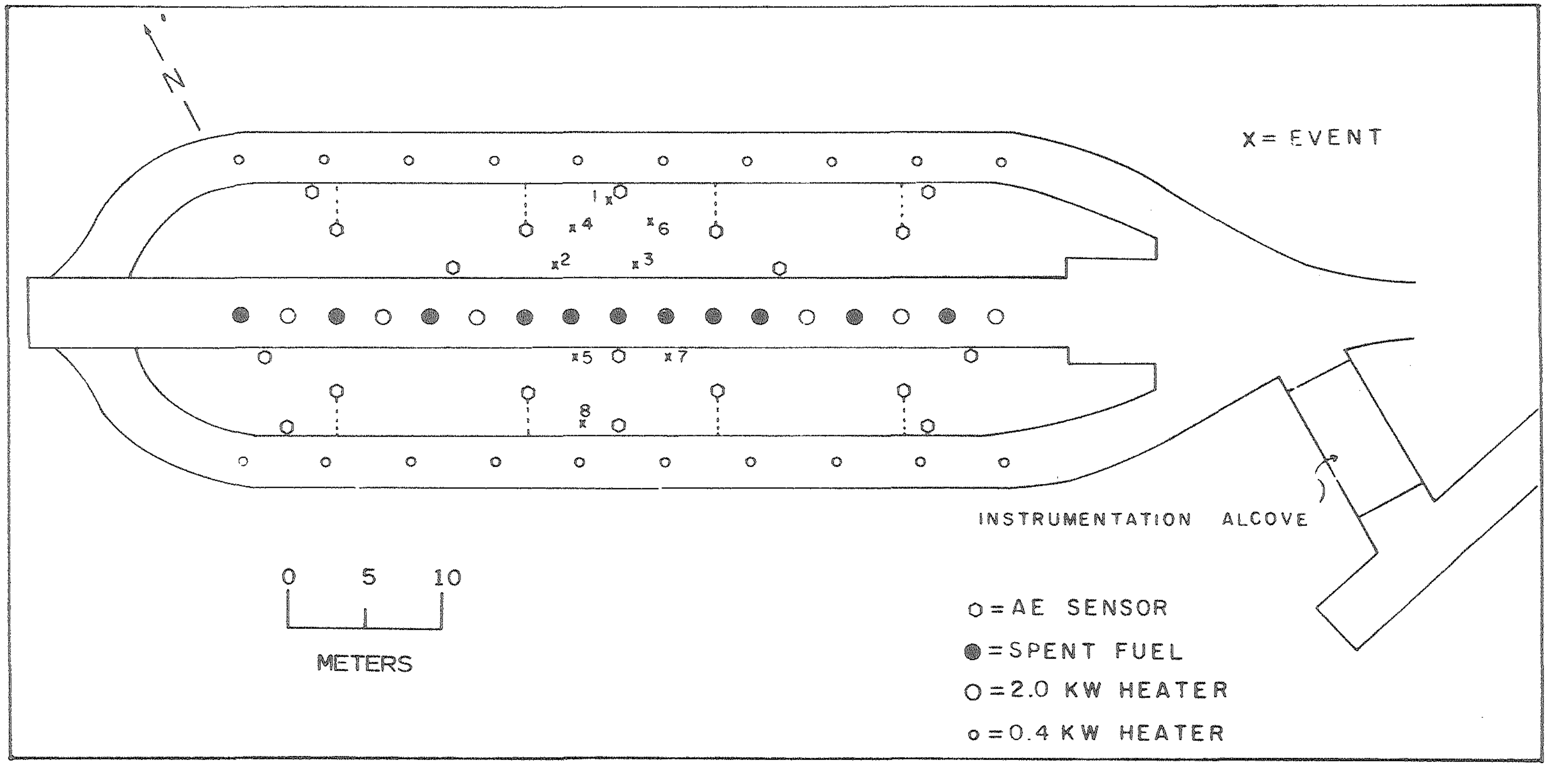
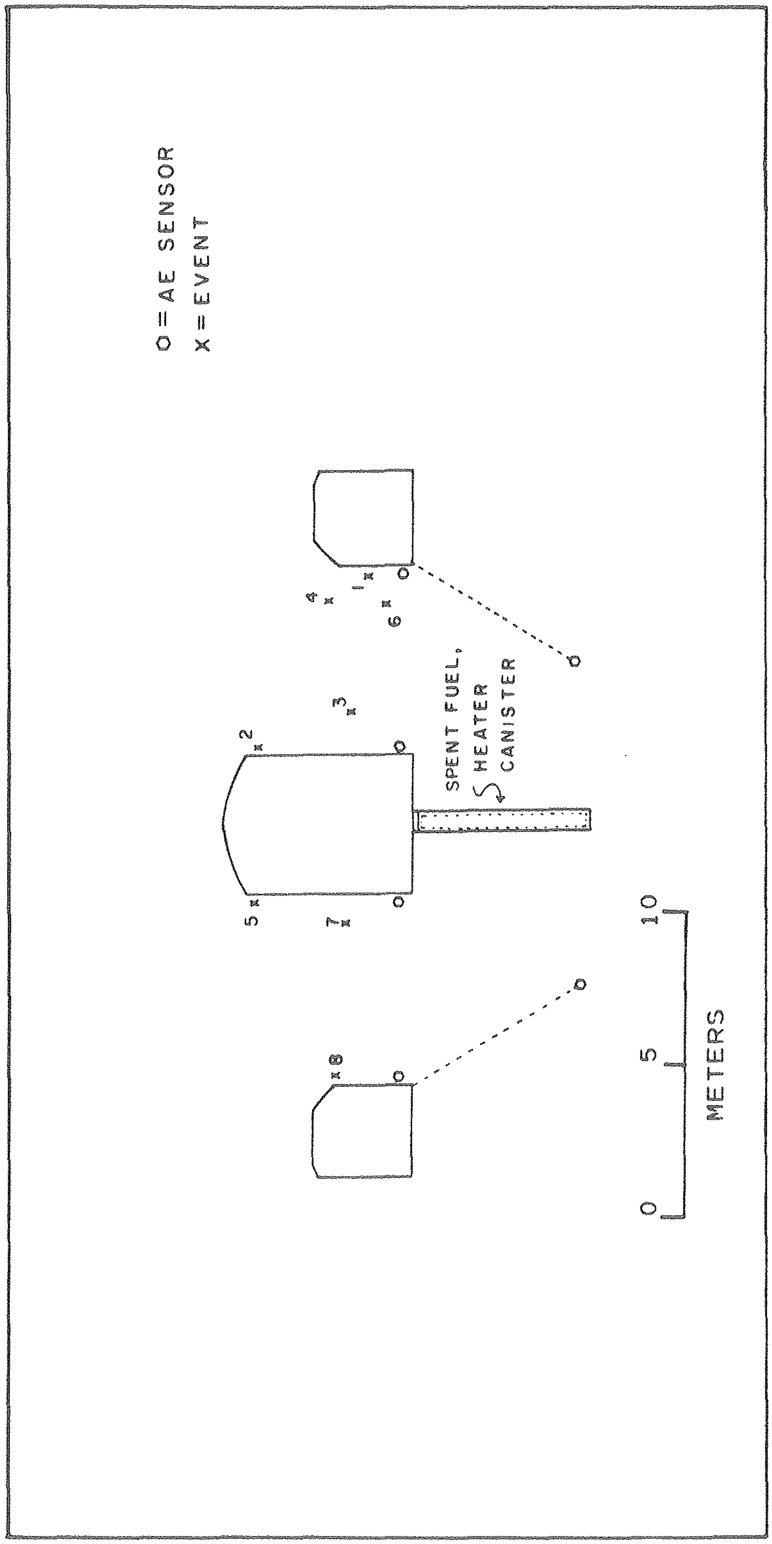


Figure 4a



XBL 8010-12309A

FIGURE 5a



XBL 8010-12310A

FIGURE 5b