CONF-760513--2

LA-UR-76-493

MASTER

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AUTHOR(S): B. R. Dennis, J. H. Hill, E. L. Stephani, and B. E. Todd

SUBMITTED TO: 22nd International Instrumentation Symp.
San Diego, CA
May 1976

los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

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DEVELOPMENT OF HIGH-TEMPERATURE ACOUSTIC INSTRUMENTATION FOR CHARACTERIZATION OF HYDRAULIC FRACTURES IN DRY HOT ROCK

Bert R. Dennis
James H. Hill
Evon L. Stephani
Billy E. Todd
Geothermal Energy Group
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545

ABSTRACT

The primary objectives of the post hydraulic fracture experiments in Geothermal Test Hole No. 2 are to study methods of measuring the location, orientation, and shape of the crack and to determine the stability of pressurized fracture systems. Detection of fracture dimensions and orientation of the geothermal reservoir is important for creating and understanding the operation of a dry hot rock energy-extraction system. These objectives require development of downhole instrumentation capable of characterization of hydraulic-fracture systems in high-temperature and high-pressure borehole environments. The development of the downhole instrumentation must emphasize reliability of measuring devices and electromechanical components to function properly at borehole temperatures of 250°C and pressures of 690 bars (10,000 psi).

INTRODUCTION

Large-scale commercial use of geothermal energy began in 1904 when natural steam from wells in the Larderello region of Italy was first piped to low-pressure turbines used to drive small electric generators. Geothermal energy has since slowly expanded for use directly as heat as well as for generating electricity. Commercial use of heat from the earth's interior has so far been limited to those areas where nature has provided a geologic situation in which the heat is transported to the surface by convective circulation of steam or very hot water. The areas are located by the obvious presence of fumaroles, geysers, or hot springs.

When a geothermal reservoir produces superheated ("dry") steam, it can be channeled from a drilled hole through a centrifugal separator into a turbogenerator to produce electrical power. The geothermal power plants at Larderello, Italy and The Geysers in northern California employ such natural dry steam to produce relatively clean, economical power.

Naturally hydrothermal systems in which the reservoir fluid is hot water (liquid-dominated systems) are much more numerous than are those in which it is dry steam. Large-scale development of "liquid-dominated" geothermal systems for generating electricity, however, has been undertaken only at Wairakei, New Zealand and Cerro Prieto, Mexico. The use of subterranean hot water on a large-scale basis for space heating is found only in Iceland, Hungary, and the Soviet Union, although there are smaller developments at several other places around the world[1].

At sufficient depth, rock hot enough to be potentially useful as an energy source exists everywhere. In many places, dry hot rock is at depths shallow enough to be reached at moderate cost with existing drilling equipment. A recent survey of available regional heat-flow data in the United States indicates that about 7% of the Western Heat-Flow Province (about 95,000 square miles in 13 western states) contains dry hot rock at temperatures above 290°C at depths of 5 km (16,400 ft)[2].

For the last 4 years, the Los Alamos Scientific Laboratory (LASL) has been actively investigating the potential for extracting geothermal energy in those areas of the United States that contain dry hot rock at moderate depths. A man-made geothermal reservoir would be formed by drilling into an identified region of suitably hot rock and creating a very large surface area for heat transfer by use of a large-scale hydraulic fracturing technique. A circulation loop would be formed by drilling a second hole and intercepting the top of the fractured region. The heat contained in this reservoir would be brought to the surface by the buoyant circulation of water. The water in the loop would be pressurized at the surface to maintain the liquid phase, thereby increasing the rate of heat transport up the withdrawal hole as compared to that of steam (Fig. 1).

Preliminary experiments and analyses indicate that thermal stresses created by cooling of the hot rock may gradually enlarge the fracture system and extend the useful lifetime of the original reservoir far beyond the planned 15 years.

LASL'S GEOTHERMAL ENERGY PROJECT

The initial geothermal source demonstration presently being conducted by LASL is located on the Jemez Plateau in that part of the Rocky Mountains extending into northern New Mexico. As the result of relatively recent volcanic activity[3], a large amount of heat is still retained in the rock underlying the area within a few kilometers of the surface. On the basis of extensive studies and field experiments[4], the "Fenton Hill" site (about 32 km west of Los Alamos) was selected for development of the first dry hot rock energy experiment. The primary objective of the dry hot rock geothermal energy extraction experiment is to investigate and demonstrate the techniques of drilling into hot granitic rock, fracturing it by hydraulic pressure, producing connected circulation loops, and then circulating water to extract the heat and transport it to the surface. The field studies will include research and development in geochemistry, geophysics, heat flow, seismology, environmental effects and other areas related to employing an economical and environmentally acceptable energy extraction system.

The first exploratory borehole drilled at the Fenton Hill site was designated Geothermal Test Hole No. 2 (GT-2). Drilling began on February 17, 1974 and the Precambrian granitic surface was reached at 733 m (2404 ft) on March 30[5]. Drilling continued in the granitic basement rock to a depth of 2042 m (6700 ft). Following the first drilling phase, a series of experiments was conducted to study the nature and physical behavior of the hydraulic fractures created in the granitic section of the borehole from 1928 to 2042 m (6326 to 6700 ft). Various diagnostic logging operations were performed by well-logging service companies during the drilling and testing phase [6]. LASL instrumentation was designed to measure rock breakdown and crack-extension pressures in the borehole, where bottom-hole temperatures at this depth reached 145°C[7].

Upon completion of the series of experiments at the intermediate depth, GT-2 was drilled to a final depth of 2932 m (9619 ft) on December 22, 1974 [8]. Various diagnostic logging operations were again performed by the well-logging service companies, although many problems with equipment failures were experienced as the bottom-hole rock temperature reached 197°C. A number of pressurization experiments was conducted to determine the permeability of the rock at the bottom of GT-2 and to investigate the extent of any natural fracture systems that might already exist. On March 27, 1975, a small hydraulic fracture was formed at the bottom of the borehole with an estimated radius of 30.5 m (100 ft) and a volume of 3028 liters (800 gal). The face permeability of the fracture was calculated to be 0.3 microdarcy. Numerous experiments and measurements were conducted in various zones extending from 2789 m (9150 ft) to the bottom of the borehole. A series of hydraulic-fracture-initiation, fracture-extension and pumping experiments was conducted in these zones to determine principal tectonic stress, stress variations, and the leak-off rate of the fracturing fluid. Measurements were performed during these experiments to characterize the fracture and to determine stability of the pressurized fracture systems. A fracture near the bottom of GT-2 was eventually extended to a radius of about 120 m (400 ft).

Drilling began on the first energy extraction borehole (EE-1) on May 26, 1975. It was completed in October at a depth of 3064 m (10,053 ft) and a measured bottom-hole temperature of 205.5°C. The downhole circulation loop was completed by employing directional drilling techniques to turn the EE-1 borehole to intercept the fracture created in GT-2 (Fig. 2). It was important to obtain the dimensions and orientation of this fracture to achieve intersection of the fracture system with the second borehole. Mapping the fracture/reservoir was also important to develop understanding of the flow and heat-transfer properties. Development of downhole instrumentation capable of characterizing the hydraulic fracture system in the high-temperature and high-pressure borehole environment was therefore required.

BOREHOLE ACOUSTIC MEASUREMENTS

The acoustic signals generated by a seismic source consist of two types of body waves. The compressional waves (P-waves) propagate parallel to the direction of particle displacement throughout the media. Since gases, liquids, and solids oppose compression, the P-waves can propagate through them. The transverse or shear waves (S-waves) propagate in the shear mode or perpendicular to the direction of particle displacement in solids. Since gases and liquids have no rigidity and cannot oppose shearing, the S-waves cannot be propagated through them. In any given solid medium, compressional waves travel at a higher velocity than the shear waves[9].

These properties exhibited by acoustic energy prompted LASL to pursue acoustic techniques as one method of mapping the fracture system and to determine the relative trajectories of the two boreholes. A downhole triaxial geophone package is employed to detect acoustic signals from discrete fracturing events as the hydraulic fracture is extended. Signals recorded from the oriented downhole triaxial geophone system are analyzed to determine the location of the events producing each signal. The relative positions of the two deep boreholes as a function of depth may be determined by use of acoustic ranging techniques. A seismic signal generated in one borehole is detected by the oriented triaxial geophone located at a known depth in the second borehole. The measured travel times of the acoustic waves and analysis of first motions at the geophone positions confirm the relative positions of the two boreholes.

DOWNHOLE INSTRUMENTATION

The most severe limitations to the use of measuring equipment in the geothermal well are associated with the high-temperature and high-fluid-pressure effects on the instrumentation cable and associated cable-head assemblies [7]. Commercially-available armored instrument cable uses seven Tefzel-insulated conductors. The conductors are wrapped around a filled core to insure uniform circular construction. The weight-supporting steel armor also serves as the electrostatic shield. The cable used to position the LASL downhole geophone package in the borehole is rated for operation at temperatures above 200°C.

Initial attempts to use acoustic methods in the boreholes employed high-temperature geophones* mounted

*Walker-Hall-Sears of Houston, Texas Model Z-3 modified for high temperature: coil resistance, 730 ohms; natural frequency, 6 Hz; intrinsic sensitivity, 1.2 V/in./sec; damping, 76% of critical.

in a cradle assembled in a multipurpose instrumentation package (Fig. 3). Coupling into the uncased (open) wall depended on the vertical tilt of about 5 degrees of the wellbore and a length of the downhole sonde sufficient to allow at least one point of contact. Early tests revealed several problems with this first assembly. The geophone output was not adequate to drive the long signal lines for the microseismic events encountered at depth; additional downhole gain was required. It was also apparent that a more positive coupling of the sonde to the borehole wall was necessary for increased response to the microseismic events generated during fracture extension.

Geometric constraints imposed upon the outside dimensions of the downhole sonde place severe restrictions on the space available for instrumentation. Pressures up to 621 bars (9000 psi) are possible at depths of 3048 m (10,000 ft), the summation of a 276-bar (4000-psi) hydrostatic head plus a 345-bar (5000-psi) pumping capability. The high pressure combined with the high temperature causes rapid deterioration of exposed components such as o-ring seals and electrical feed-throughs.

The downhole geophone package as it has evolved over the past year is shown in Fig. 4. This diagram describes the physical layout of the coupling mechanism (arm and actuating device), the instrumentation housing, and the cable-head assembly. The body of the sonde is made from AISI 4340 steel which has been heat treated to insure a yield strength of 827.4 bars (120,000 psi). The entire package is 3.55 m (12 ft) in length with a maximum diameter of 9.2 cm (3-5/8 in.). The assembled package weighs 762 kg (120 lbs).

Figure 5 shows the coupling system used to force the sonde against the borehole wall. The arm-actuating device is driven by a small dc motor with a built-in gear reduction of 647:1. The output of the motor is further reduced by a lead screw mechanism. The motor has a rated torque of 214.3 Nm (186 in.-lbs) and is specified for continuous operation at 125°C. The motor was tested for intermittent duty (several hours) at 200°C and has operated satisfactorily downhole. Total travel time of the arm from the fully retracted position, enclosed in the sonde housing, to the fully extended position (22.9 cm or 9 in.) is approximately 2 min. A balanced piston has been designed into the actuating mechanism to equalize loading in both directions. The total force of the arm against the borehole wall is about 90.7 kg/ft (200 lbs). The actuating linkage includes a shear pin to release the extended arm should the motor fail downhole.

Figure 6 is a schematic diagram of the downhole geophone sonde showing the arrangement of the geophones, dewar, and amplifier package, actuating motor and cable-head connectors. The Viton o-ring seals are specified to meet the borehole requirements of pressure and temperature. It has been found, however, that this elastomer tends to become brittle when exposed to the downhole environments for several hours and must be replaced for each experimental insertion.

To increase output signal strength and improve the downhole signal-to-noise ratio, an operational amplifier circuit was used as shown in Fig. 7. The Harris 2620 operational amplifier was tested at 200°C for several 24-hr periods and operated continuously with only slight degradation in specifications. Four geophones were arranged in series for each orthogonal set and were also wired in parallel with a high-temperature resistance equal to the geophone coil resistance. Polarity of first motions was carefully observed for each geophone during fabrication of the cradle assembly (Fig. 8) to insure signal enhancement. This configuration allowed for an increase in gain by a factor of 2 and also increased the reliability of the geophone package. The frequency response curves shown in Fig. 7 correspond to the open-loop gain of the amplifier (A), the actual amplifier response with a gain of 100 (B), and the response of the system driving the armored instrument cable (C).* The instrument cable introduced another serious limitation for the downhole amplifier array since only seven conductors were available for wiring the triaxial package as shown in Fig. 9. The common reference conductor and common power supply resulted in poor common-mode rejection and excessive crosstalk.

The alternative approach to the amplifier package required a method to cool a battery-operated differential amplifier for a period of 12 hrs in the 200°C environment. The schematic of a Burr Brown M3670 differential amplifer is shown in Fig. 10. The amplifier and associated battery pack were potted with a Dow Corning silicone-rubber epoxy and housed in an ice-filled glass dewar (Fig. 11). Providing the dc power for downhole amplifier operation allowed for complete isolation of each geophone system, thereby reducing crosstalk and ground-loop problems. Balance of each amplifier was achieved while it was submerged in an ice bath, thus reducing dc drift during downhole operations. The gain of this amplifier was set at 1000 and the response is shown in Fig. 10, Curve A. Curve B describes the response of the amplifier driving the instrument cable. Figure 12 shows the geophone cradle and dewar package ready to be assembled in the pressure-sealed downhole sonde. An additional refinement was the encapsulation of the amplifier and battery pack in a solid brass tube (Fig. 13), increasing the volume of ice in the dewar and extending the downhole lifetime by several hours.

Signals from the geophones were conditioned in a surface recording facility through a differential amplifier and fm multiplexed for high-frequency recording on analog magnetic tape. The tapes were reproduced on a wideband recorder and the signals processed in a Hewlett Packard 5451B Fourier Analyzer and Data Processor.

FIELD RESULTS

To determine the spatial orientation of hydraulic fractures, several experiments were conducted employing the downhole geophone sonde. During inflation

*Cable electrical parameters were measured at 280 ohms per conductor, 100 megohms conductor to armor, 0.54 μF capacitance per conductor pair, and 5.75 mH inductance per pair.

of the fracture originating in GT-2, discrete acoustic signals generated by microseismic events along the plane of the fracture were detected by the geophones locked into the rock wall in EE-1 at a depth of 2827 m (9277 ft). The signals shown in Fig. 14 were recorded from one such event. The signals were processed to produce Lissajou figures describing the particle velocity of the arriving compression phase. The geophones, H1 and H2, record the particle velocity in the horizontal plane (Fig. 15). The angle of the Lissajou pattern described by the passing signal defines the source direction in the horizontal plane. Similar analysis using the response of the vertical geophone completes the spatial determination of the source direction. The distance from the geophone sonde to the focus of the event is determined by measuring the time difference between the arrivals of the compressional phase and the shear phase since the propagating velocities of the respective phases are known. Preliminary analysis of 30 events detected during this experiment resulted in the location of a hydraulic fracture approximately 24.4 m (80 ft) from the sonde position with a lateral extension of at least 152 m (500 ft) in a direction N27°W (Fig. 16). Additional inflation and extension experiments employing the downhole geophone sonde will provide better resolution of the shape and orientation of the fracture.

Acoustic ranging experiments were conducted for the purpose of determining the relative position of GT-2 with respect to EE-1. The downhole geophone sonde was deployed in GT-2 at predetermined depths to record the acoustic signals generated in EE-1 by firing a series of high-temperature detonators at equivalent depths in EE-1. A single vertical geophone, placed in the downhole detonator package, established firing times. Figure 17 is an example of the signals recorded by the geophone package in GT-2 during the ranging event. Again, since the compressional wave velocity in the local rock is known (5.85 km/sec), the distance from the source (detonators) and the geophone sonde in this instance was measured to be 9.2 m (30.2 ft).

CONCLUSIONS

The acoustic method to map hydraulic fractures in deep geothermal boreholes is one of several methods now under investigation at LASL.* The downhole acoustic experiment has proven to be successful and has established the priority to develop more advanced techniques. One area of major concern is the true orientation of the seismic sonde downhole. It is important to determine the position of the triaxial geophone cradle once the instrument package is locked into the borehole wall. Several techniques including a magnetic compass photographic device, gyroscope survey, and plumb-bob alignment have been used with very limited success, primarily due to the high-temperature effects encountered in the borehole. Further development of a downhole orientation device has been assigned the highest priority. This development includes not only the problems associated with making reliable measurements in the hostile environment encountered in the geothermal borehole, but also demands a continuous updating and refinement of new analytical techniques.

Much of the hardware presently employed in the experimental program has reached maximum operating temperature specifications. New materials must be incorporated into the design of components such as motors, transducers, seals, cable and head assemblies, if future measurements at depths approaching 12,500 ft and bottom-hole temperatures exceeding 250°C are to produce reliable data.

*Methods now under development at LASL to map hydraulic fractures in deep geothermal boreholes include spontaneous electrical potential, induced electrical potential, hole-to-surface electrical resistivity, and vertical-coil induction techniques.

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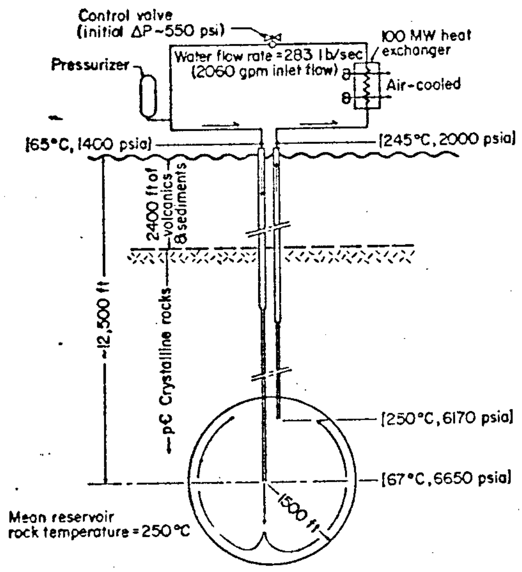


FIGURE 1. Dry Rock Geothermal Energy System

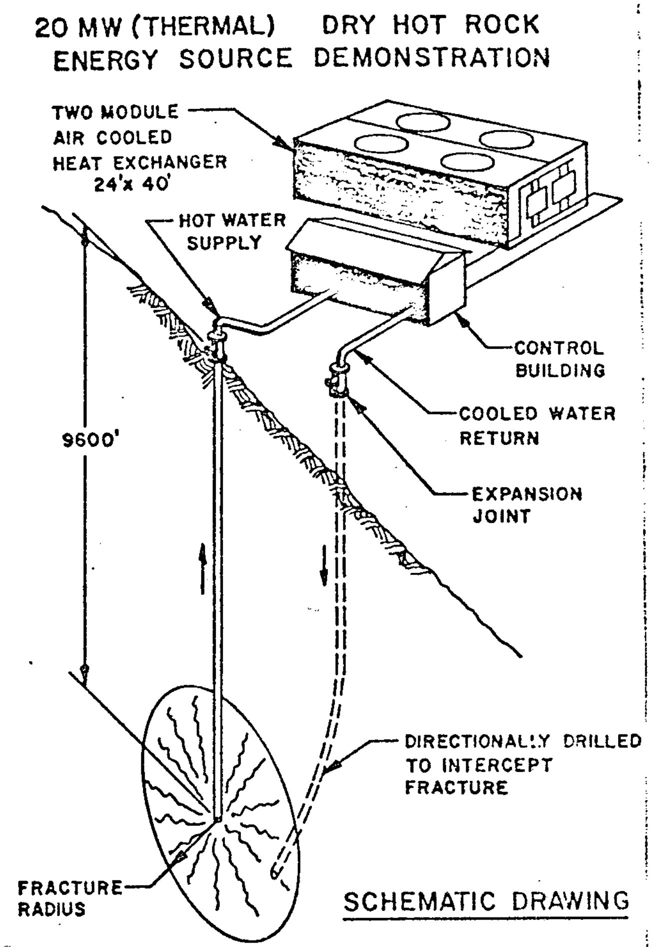


FIGURE 2. Intermediate Dry Hot Rock Energy Extraction System

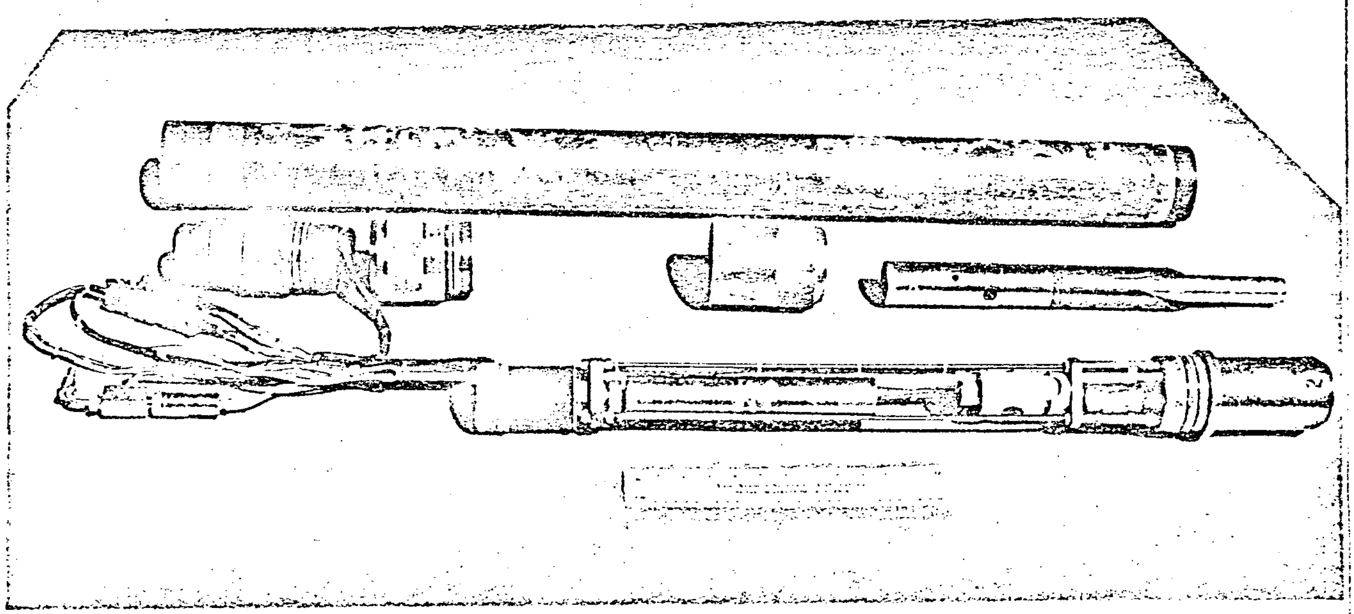


FIGURE 3. Multipurpose Downhole Instrumentation Sonde

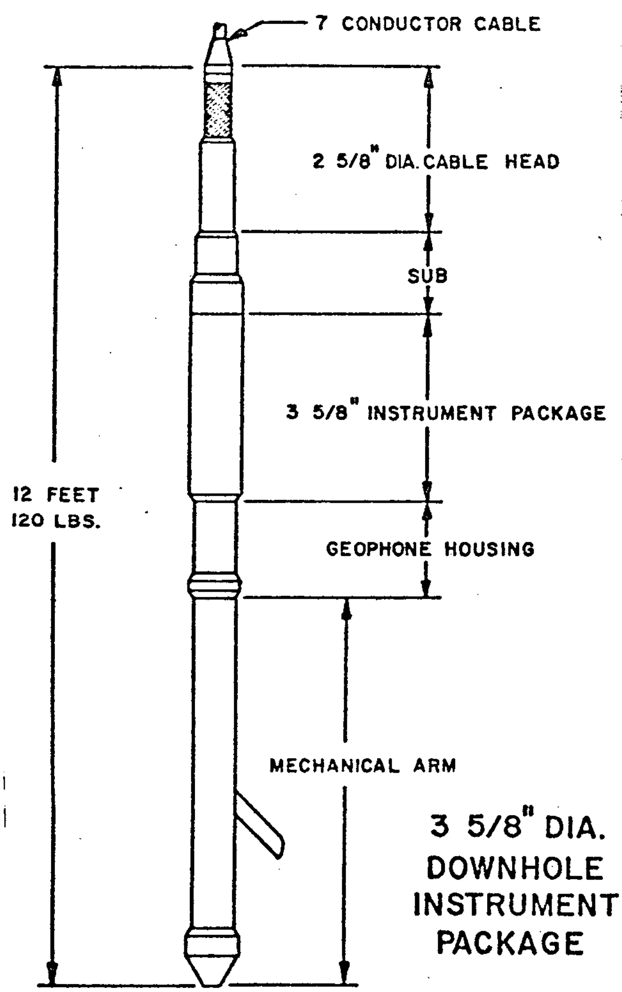


FIGURE 4

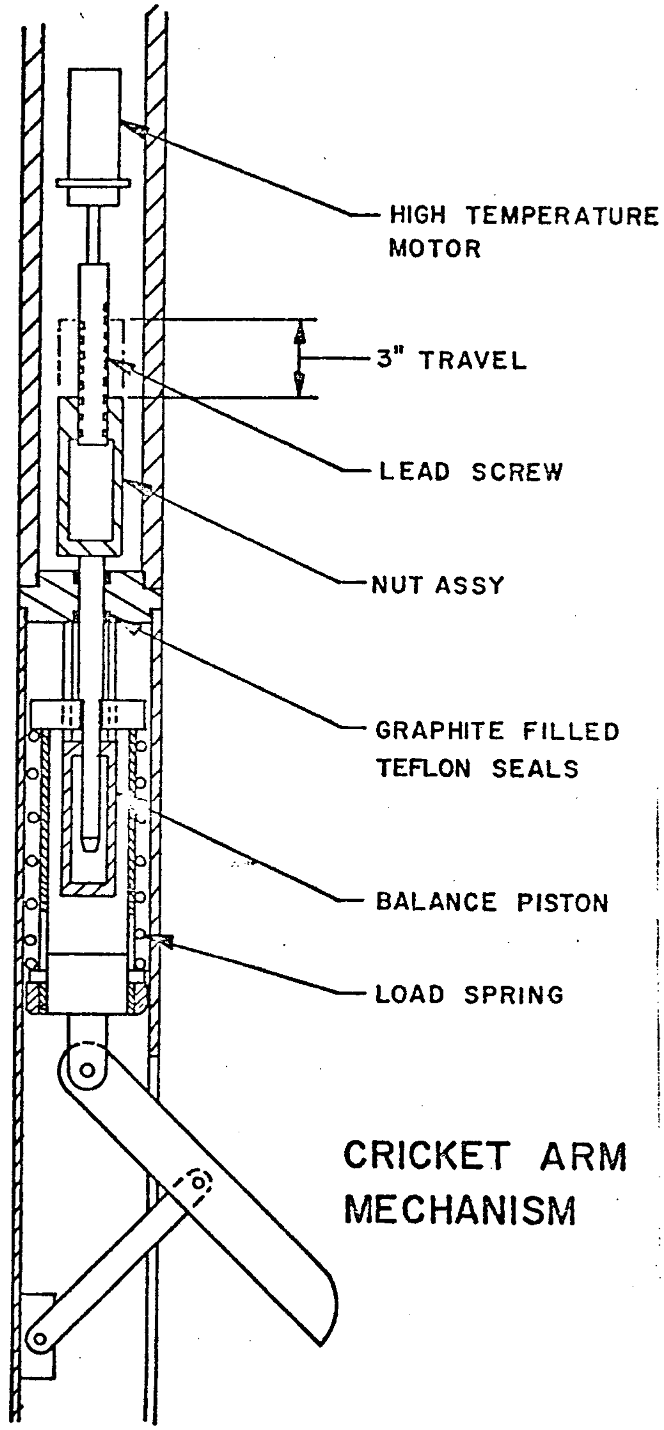


FIGURE 5. Locking Arm and Actuating Device in Downhole Instrument Sonde

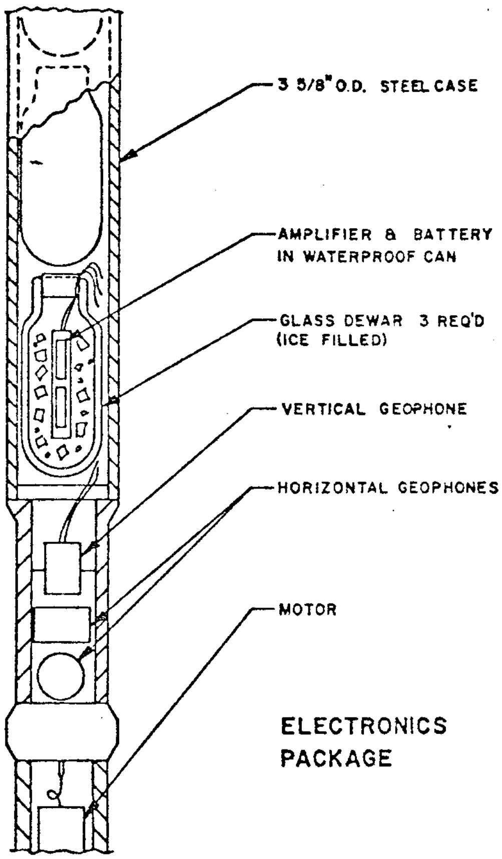


FIGURE 6. Electronics Package in Downhole Instrument Sonde

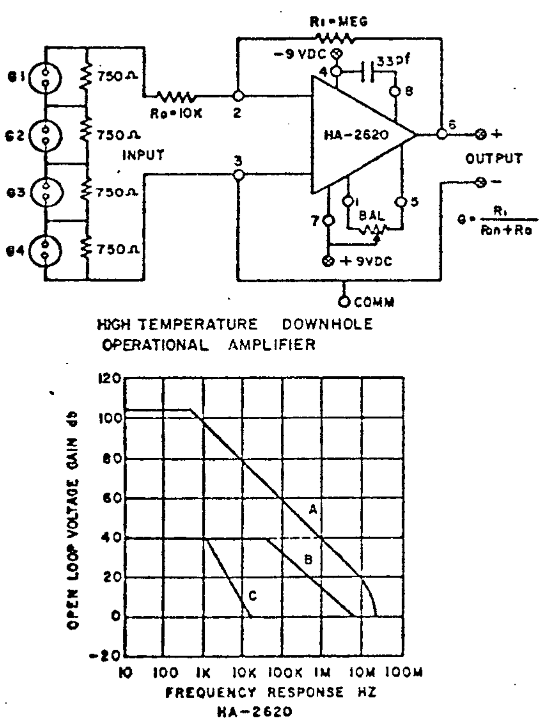


FIGURE 7. High Temperature Downhole Operational Amplifier

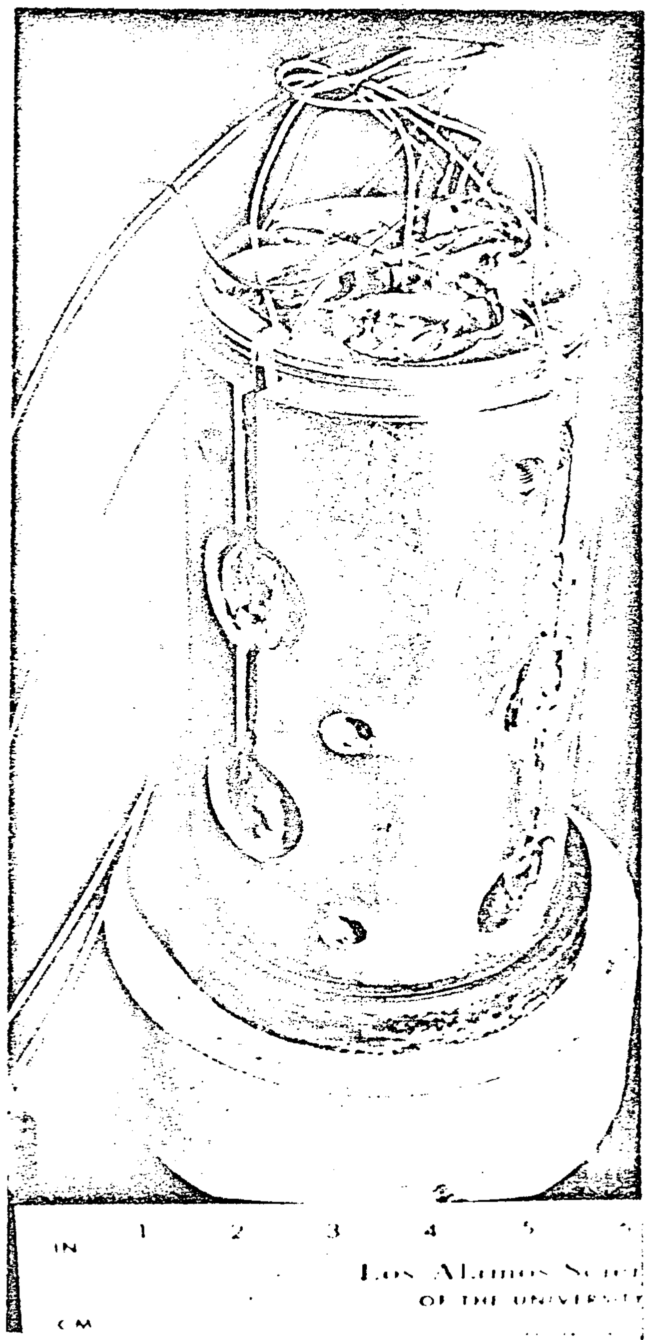


FIGURE 8. Downhole Geophone Cradle Assembly

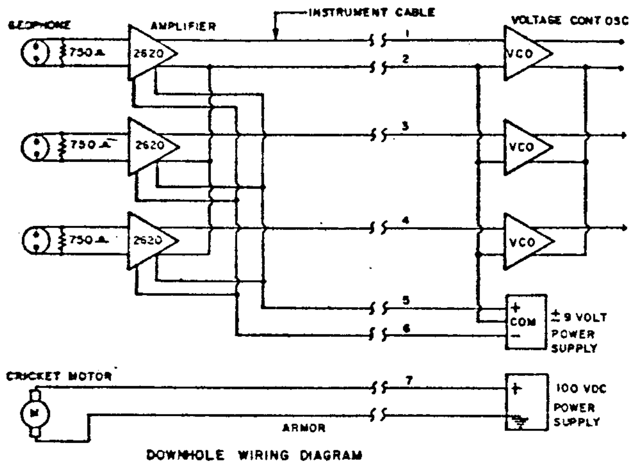


FIGURE 9. Operational Amplifier Assembly

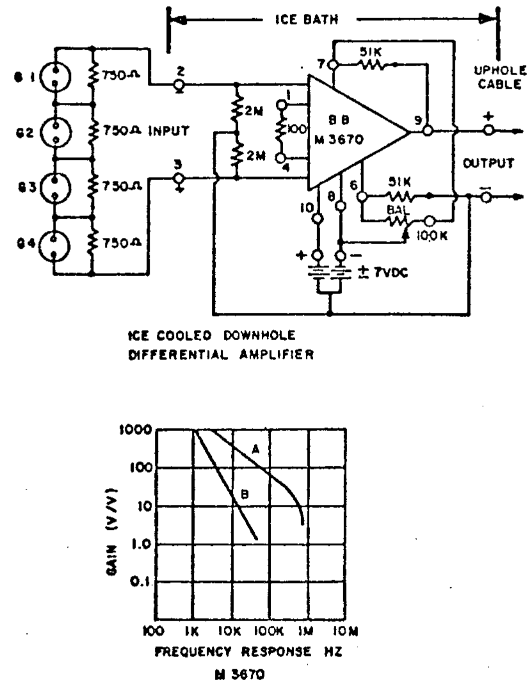


FIGURE 10

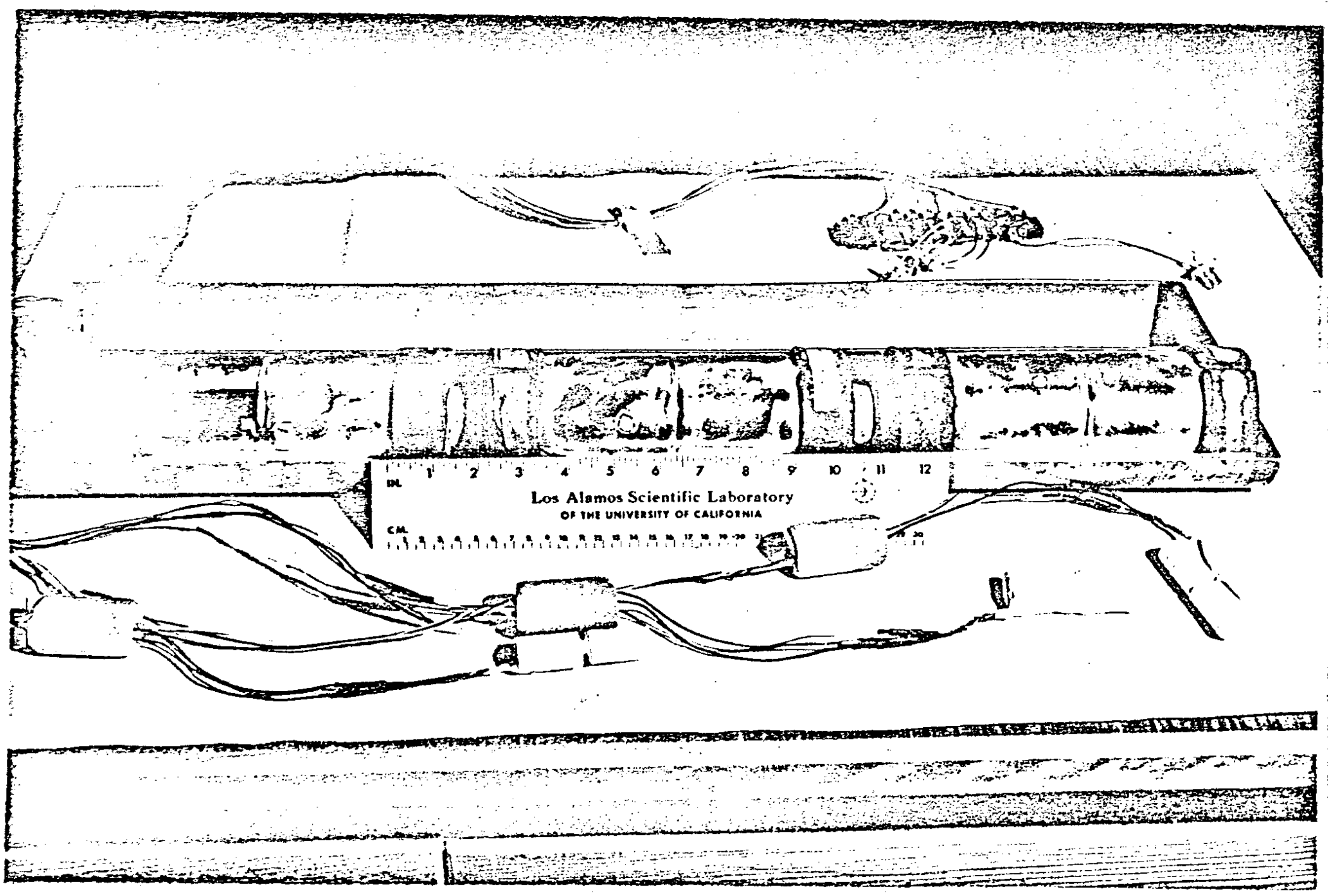


FIGURE 11. Dewar Assembly With Amplifiers and Battery Pack

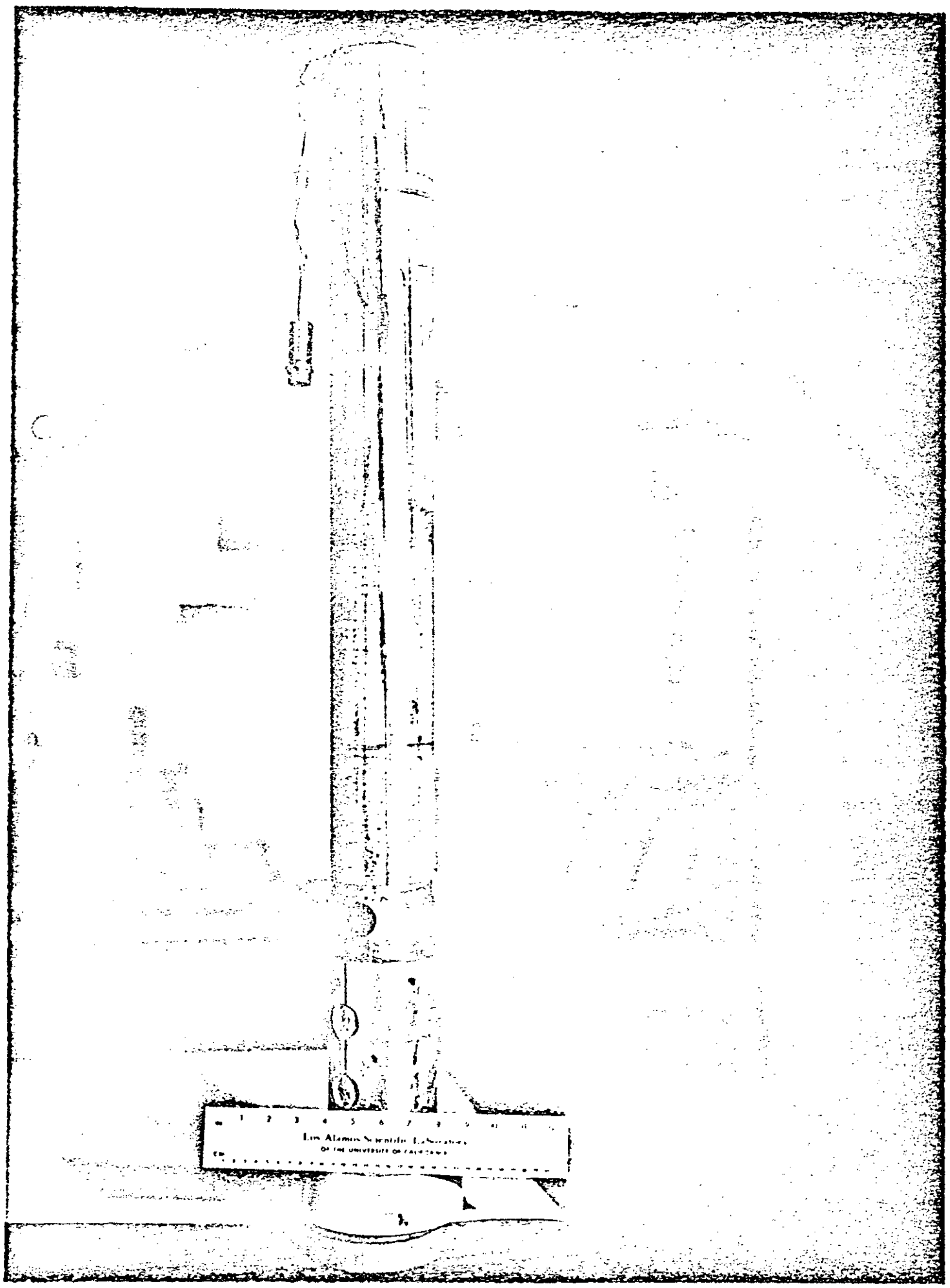


FIGURE 12. Acoustic Cradle and Dewar Assembly

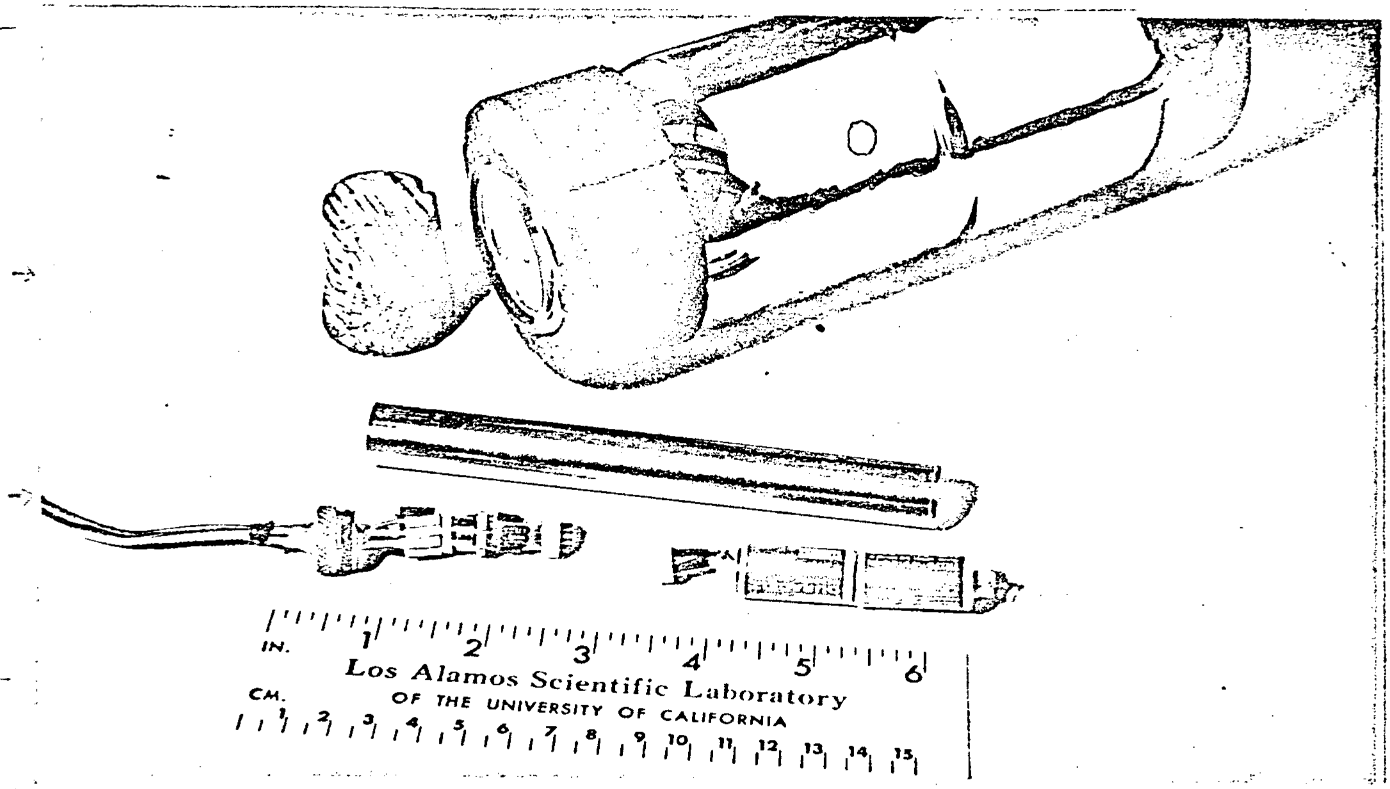


FIGURE 13. Slimline Amplifier and Battery Pack

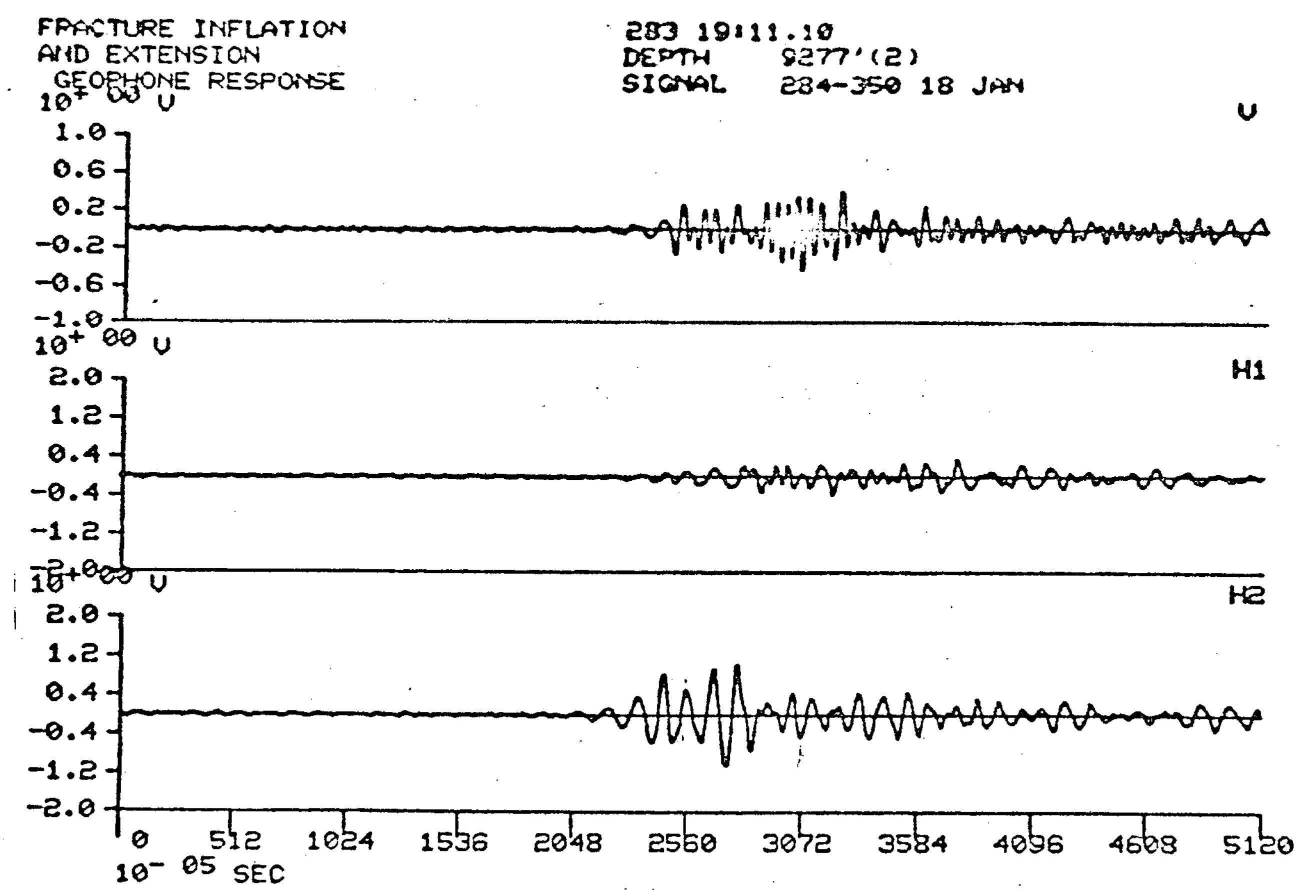


FIGURE 14. Acoustic Signals from Fracture Inflation

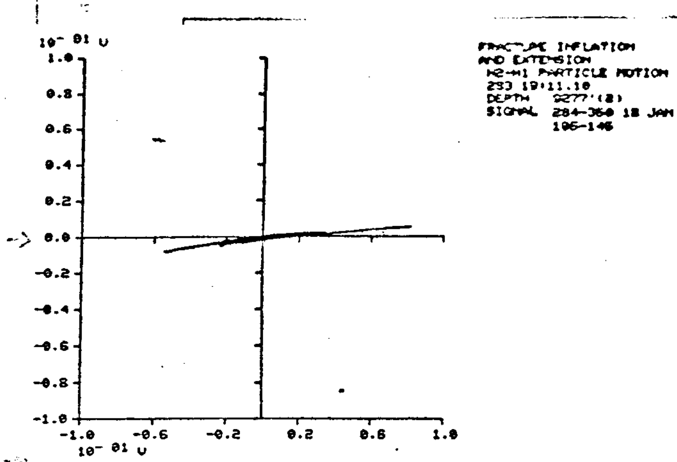
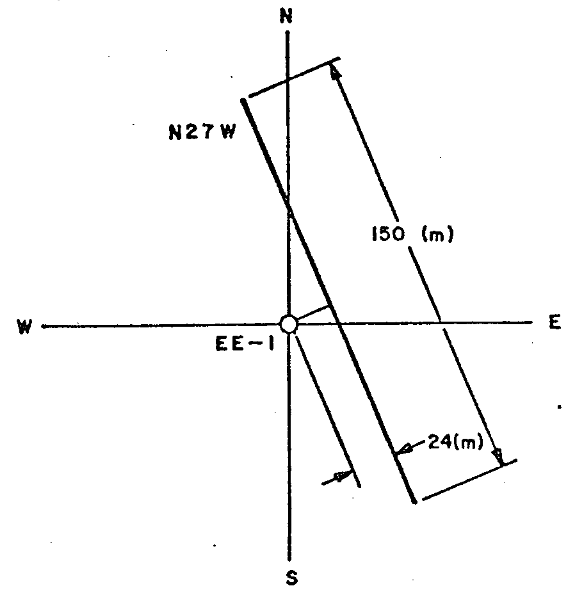


FIGURE 15. Lissajou Figure H1-H2 Plane



FRACTURE ORIENTATION
IN HI-H2 PLANE
DEPTH 2827 (m)

FIGURE 16

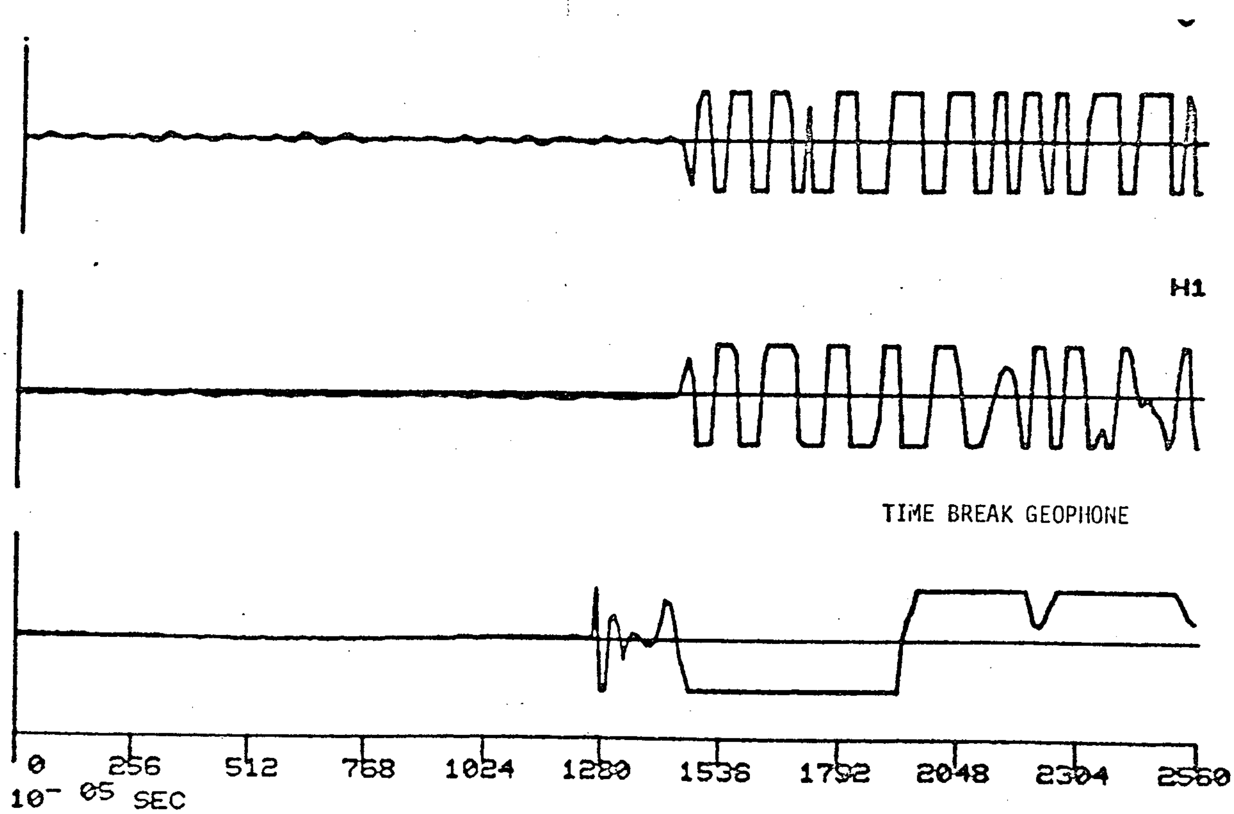


FIGURE 17. Acoustic Ranging EE-1/GT-2 Geophone Signals