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BOREHOLE SURVEY INSTRUMENTATION DEVELOPMENT FOR GEOTHERMAL APPLICATIONS

by

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ABSTRACT

The creation and subsequent study of hot dry rock geothermal reservoirs requires sophisticated tools and instruments that can function for relatively long periods of time in the hostile downhole environment. Detection of fracture dimensions and orientation of the geothermal reservoir is critical for the successful completion of the hot dry rock energy extraction system. The development of downhole instrumentation capable of characterizing the hydraulic-fracture systems must emphasize reliability of measuring devices and electro-mechanical components to function properly at borehole temperature exceeding 275°C and pressures of 69 MPa (10,000 psi).

INTRODUCTION

Downhole instrumentation to "map" the hydrualic fracture system and study man-made reservoirs is critical to the success of the hot dry rock energy system. This instrumentation must operate continuously for periods of up to 12 h in the high-temperature/high-pressure environment. The development of this equipment depends upon the advancement in technology to upgrade components such as transducers, seals, motors, connectors, feedthrough devices, high-temperature electronics, and other electrical/mechanical equipment for operations in the hostile geothermal environment. The design criteria for the instruments developed for this program specify continuous operation for at least 12 h at 275°C and 69 MPa (10,000 psi).

CABLEHEAD ASSEMBLY

Instruments used in reservoir assessment and for fracture mapping often must remain downhole for periods of 12 h in the high-temperature/high-pressure geothermal borehole environment. Communications between the downhole instrument and the surface recording facility is by a high-temperature multiconductor instrumentation cable terminated downhole at the cablehead assembly. The cable must maintain mechanical and electrical integrity of the conductors for the duration of the test. Indeed, the development of high-temperature wellbore instruments capable of functioning at 275°C is constrained by the quality of the electrical connection between the subsurface electronics and the surface recording equipment.

The cablehead design implemented at LASL is rated for continuous service at 275°C (Archuleta, et al., 1978). The primary function of the cablehead is to provide a cable-to-sonde electro-mechanical coupling device, which protects the electrical conductors from the high-pressure and high-temperature fluid environment. The cablehead also establishes a transition area from the downhole fluid, high-pressure environment to a dry, low pressure instrument chamber. It also provides a protected area for splicing the cable conductor ends to the high-temperature bulkhead. Should the instrument sonde become lodged in the wellbore, the cablehead is designed to allow separation of the sonde and the cable. The fishing bell housing then provides a positive gripping area for overshot fishing tools for retrieval from the borehole.

The standard cablehead now in use at Fenton Hill is 53-mm (2-1/8-in.) diam and 0.889-m (35-in.) long (Figure 1). The basic design has been adapted to construct cablehead assemblies of 70-mm (2.75-in.) diam and a 45-mm (1.75-in.) diam.

Multipiece design is used in the splice cavity and cable packoff area for ease in disassembly and reheading. Most components are made from high strength (4340) steel, heat treated to 1.38 X 10^3 MPa (200,000 psi) tensile strength allowing service to 103 MPa (15,000 psi).

A free-floating swivel and a quick-change, 7-pin electrical connector at the sonde-to-cablehead surface allows connection without rotation of the joined parts or coiling of the electrical conductors.

DOWNHOLE TEMPERATURE SURVEY MEASUREMENTS

Temperature measurements have been used extensively as one method to study the man-made geothermal reservoir. The temperature probe is one of the less complex wellbore survey tools that is readily fielded to allow on-line analysis of changing conditions.

A practical borehole temperature survey instrument utilizes a thin-walled stainless steel thermistor probe as the sensor. The thermistor is essentially a semi-conductor that behaves as a temperature sensitive electrical resistance which provides a high degree of resolution not available in other transducers. Thermistors are well suited for continuous measurements in temperature environments exceeding 300°C. The resistance-temperature response is, however, quite non-linear and varies from one type of thermistor to another. Each temperature probe must be carefully calibrated. The borehole temperature sonde presently in use at Fenton Hill is shown in Figure 2. The sonde contains a thermistor probe in a 1/8-in.-o.d. stainless steel sheath (Conax TH15-SS6-E-TI-MK .062). The probe has been carefully calibrated in an oil bath at six discrete temperatures ranging from 0° to 205°C. The temperature resistance characteristics are linearized by the function:

$$T = \frac{C_1}{\ln(R_T)+C_2} - C_3$$

The coefficients are determined from the calibration data by a least squares for the above equation. The method of solution iterates on C_1 until the standard error in T converges to a minimum value.

The long-term residence in the high-temperature environment of the geothermal borehole, no electronics are used in the sonde. Instead, a constant current source is used to excite the thermistor over the long lines as shown in Figure 3. The constant current supply provides 500 μ amps through a nominal 1000 Ω series resistor. A precision 10,000 Ω resistance is connected in parallel with the thermistor resistance to limit the range of voltage generated across the thermistor allowing a higher constant current excitation for greater sensitivity at the higher temperatures thus lower resistance values.

The measured temperature is then computed in the HP9830 calculator from the linearized equation for T where R_T is derived from the constant current measured through R_1 and the voltage drop across the thermistor R_T. The maximum error in the system is 0.26°C and the temperature resolution is 0.01°C.

A program to survey the temperature in GT-2B during the Phase I 1000-h circulation experiment was undertaken with some concern for downhole equipment performance. The area to be surveyed was at a depth of 2400 m (8000 ft) to 2700 m (8900 ft). The temperature sonde would be lowered into the GT-2 wellbore through a pressure lock which would allow retrieval of the tool should failure occur in the instrument, or more likely in the associated cablehead assembly. The cablehead was designed and fabricated at LASL specifically for long-term residence in the high-temperature, high-pressure environment. The temperature survey was taken over the interval of interest every 4 h during loop start-up. This time interval was increased until a logging schedule of once per day was established. The sonde was positioned at a depth of 2600 m (8550 ft) between each survey and data continuously sampled at this stationary depth throughout the Phase I operation (Tester, et al., 1979). The temperature sonde and associated cablehead met all the performance criteria for a total of 1056 h in the bottom of the borehole.

CALIPER TOOL

The development of an independent multiarm caliper tool began with the design and fabrication of a prototype 3-arm sonde, which can readily be adapted to 6 independent arms. The arms are evenly spaced circumferentially and are capable of measuring radii from 63.5 mm (2.5 in.) to 178 mm (7.0 in.) at a common depth (Figure 4). Arm length can be varied to measure hole diameters up to 762 mm (30 in.) or can be designed for maximum sensitivity at given diamters. The arms are activated by a dc motor and can be extended or retracted on command from the surface. Should the sonde become jammed in the borehole, the lower link will buckle and permit the arms to collapse.

The caliper tool was designed to define the profile of geothermal boreholes such as those at Fenton Hill. It is sensitive enough to detect accuractely 1-mm variations along the borehole wall. It has been used to determine where a hydraulic fracture intersected the boreholes and to assess the integrity of the borehole casing (HDR Program Staff, 1979).

In the normal mode of operation, the arms are extended when the sonde is below the region of interest and the caliper is pulled up the borehole at velocities from 0.025 m/s to 0.13 m/s (5 fpm to 25 fpm). Borehole detail is lost at high logging speeds, but a general borehole contour is obtained.

The arms are spring-loaded to provide approximately 45-N (10-lb) force against the borehole wall. Motion of the arm, as it follows the hole contours, is transformed to the vertical movement of a follower rod. The vertical travel of the follower rod is then transformed to rotational motion of the external magnetic coupling with reference to the centerline of the tool (vertical axis) by use of a bead chain. The coupling's azimuthal position is determined by the use of a 350°, 5000-ohm potentiometer. The potentiometer shaft rotates with feeler-arm motion, thus indicating arm position. The three potentiometers (one for each arm) are used as voltage dividers. A surface voltage feedback system monitors downhole voltage and maintains a constant 4 V, as sensed downhole, across the resistance elements of the three potentiometers to armor. The output signal is conditioned by low-pass filters at the surface. The data are stored on magnetic disks and plotted on-line by an HP 3050B/9830 data acquisition system (Figure 5).

FLUID VELOCITY SPINNER

Study of the Fenton Hill boreholes includes investigating the flow of the geothermal fluid throughout the system. Information regarding flow rates, combined with data from the temperature tool, help to ascertain the location of hydraulic fractures. Since high-temperature (200°C) downhole flow meters are commercially available, LASL purchased one and modified it to suit the Fenton Hill application.

The LASL version of the commercial spinner tool (Figure 6) improved the sensitivity, repeatability, and resolution of the tool through modifications in several areas: the impeller size was increased from 34.5 mm (1.375 in.) to 74.2 mm (2.92 in.); the surface electronics were designed to provide better resolution and increase the analog output from 10 mV full-scale to 10 V full-scale; and a flow concentrator was designed to increase sensitivity as well as to protect the impeller. This flow concentrator does not increase the local fluid flow.

The analog output is linear to appproximately 12 V, corresponding to a fluid velocity of 1.8 m/s (350 fpm). Minimum sensitivity was measured at an initial 0.09 m/s (18 fpm) rising to 0.13 m/s (25 fpm) after 5 h of operation in the borehole (Figure 7). New surface electronics have improved resolution of ±1 fpm at constant impeller speed.

The spinner is capable of logging the boreholes vertically in either direction. This tool is undergoing tests for sustained operation at 275°C.

DEWAR (CONTROLLED-ENVIRONMENT ENCLOSURE)

The controlled-environment enclosure was designed to protect instruments from the hostile downhole environment of the geothermal wellbore. It provides housing for electrical components such as the geophone package, magnetic-ranging survey equipment, amplifiers, and inclinometers, and will house electronic multiplex equipment in the future. The dewar package is held in a LASL-designed and fabricated pressure vessel made of AISI 4340 steel, heat treated to a yield strength of 1000 to 1200 MPa (145,000 to 175,000 psi), and designed to withstand 69 MPa (10,000 psi) external pressure. The enclosure was fabricated and tested by Mechanics Research, Inc. under contract to LASL.

The dewar is the primary heat-transfer barrier. It has a large opening at the upper end to permit loading of the instrumentt package and heatsink containers. The opening is then sealed with a MIN-K plug. An interconnect cable can pass through the lower end of the dewar to an adjoining vessel if necessary.

Laboratory tests demonstrated that the dewar's instrument compartment temperature remains below 85°C for 12 h in an external temperature environment averaging 275°C. A source in the cavity dissipated 15 W of heat during each of the tests to simulate the output of an electronic package.

There are four dewar sizes to hold electronics:

External	Internal
2.20 m X 114.3-mm diam (87 X 4.5 in.)	2.13 m X 87.8-mm diam (84 X 3.46 in.)
0.96 m X 88.1-mm diam (38 X 3.47 in.)	0.91 m X 66.7-mm diam (36 X 2.55 in.)
1.80 m X 88.1-mm diam (71 X 3.47 in.)	1.75 m X 66.7-mm diam (69 X 2.55 in.)
1.82 m X 50.0-mm diam (72 X 2 in.)	1.77 m X 38.6-mm diam (70 X 1.52 in.)

DOWNHOLE INJECTOR AND GAMMA-RAY DETECTOR

Water circulation in the geothermal boreholes in studied with the injector-tracer sonde. Radioactive ^{82}Br is injected into one of the boreholes by an injector sonde developed by LASL, which delivers the radioactive material to the desired location within the borehole for release. The gamma-ray detector is mounted in the same sonde as the injector.

High-purity amonium bromide is prepared by irradiation with neutrons at a nuclear reactor in Los Alamos. The ^{82}Br has a half life of 35.4 h and its principal gamma energies are from 554 keV to 1474 keV. For irradiation, the solid NH_4Br is sealed in a quartz ampoule. To prevent irradiation of personnel working with the sonde, the ^{82}Br is transported in a lead pig. The sonde is bolted onto the upper portion of the pig, which then comes apart to become part of the sonde (Figure 8).

When the sonde has been positioned in the borehole for release, a dc motor propels a rod, which is driven into the quartz ampoule, smashing it. To flush the ^{82}Br into the geothermal fluid, 199.39 mm^3 (7.85 cu in.) of water is pushed out of the sonde, carrying the ^{82}Br with it. The gamma-ray detector then follows the path of the ^{82}Br, and is read out on surface. The electronic circuitry will be repackaged in one of the dewar enclosures, which will upgrade this sonde for operation at 275°C.

DOWNHOLE DETONATOR ACOUSTIC SOURCE

The high-temperature detonator is used as downhole acoustic source to map the hydraulic fracture and determine borehole location. This requires that the geophone sonde be used in conjunction with the detonator package to register the acoustic signals generated by the explosives. The two tools are lowered into separate boreholes. The detonator can set off 12 charges sequentially at any desired location. The firing system consists of a downhole firing module, uphole control unit, detonator rack, and high-temperature detonators (Figure 9) (Patterson, et al., 1979).

The downhole firing module includes an inverter to convert 20 Vdc to 5000 Vdc, which is then used to change a 1-μF energy storage capacitor. The energy available in the capacitor is then distributed to 12 trigger tubes, any of which may be selected by means of a diode matrix. The downhole unit requires a 6-conductor cable to accommodate the following functions: +Vdc input, common, and 4 channel-selector conductors.

The uphole unit was designed by Reynolds Industries. It consists of a variable trigger voltage and special connector to select manually any one of the 12 channels. A timer was added by LASL to control accurately the capacitor charge and automatically trigger the downhole firing module. The detonator rack has three levels, each of which will accommodate four detonators. Connections to the detonators are made through Kemon coaxial boots and feedthroughs. All the detonators (RP 84) are HNS exploding-foil type, designed to withstand high temperatures (275°C) and pressures greater than 34.5 MPa (5000 psi) and are inherently safe from accidental detonation during transit and handling.

GEOPHONE SONDE

The downhole acoustic detonator (geophone sonde) has been repackaged to utilize the controlled environment enclosure (dewar), thereby greatly simplifying field assembly and increasing the useful downhole operating time (Dennis, et al., 1976). The design also includes a downhole switching system to allow multiplexing of additional pertinent data to monitor internal dewar temperature, sonde orientation, and casing-bottom locator for depth-measurement correction (Figure 10).

The downhole amplifier circuits have been mounted on a printed circuit board and, together with the battery pack, have been inserted into the dewar assembly. The amplifier is used to establish a signal gain of 1000 to drive the surface recording equipment through the cable. The dewar assembly, as previously described, houses the electronic system. The phase-change heatsink material in the dewar has the additional advantage of a relatively high thermal conductivity. Heat conduction along the axis from the ends to the center, away from the electronic package, is through the heatsink container's copper wall. Maximum temperature difference within the flask is 4°C.

The downhole multiplex system allows intermittent sampling of pertinent data in addition to the geophone and associated amplifier outputs. The system includes two Schavitz Model LSRR-14.5 inclinometers to measure borehole slant angle referenced to the downhole sonde to provide geophone orientation. Provisions are also incorporated to measure internal dewar temperature and all downhole power supplies (battery packs).

The downhole multiplex is controlled from the surface data acquisition and control system (HP9835). The program is designed to step the downhole multiplexer by operator initiation of a keyboard command allowing the measurement cycle of auxiliary downhole data. Upon completion of this cycle (the time interval to be selected by the operator), the computer will return the multiplex to continuously monitor the geophone outputs.

INSTRUMENT SONDE TEST FACILITY

Downhole instrument sondes have been used extensively in the 200°C borehole environment. For operation at temperatures up to 275°C and pressures exceeding 41.0 MPa (6000 psi), materials and components, including seals, motors, connectors, feedthroughs, potting compounds, and other electrical/mechanical equipment, must be designed and tested to meet these more stringent conditions. The maximum test conditions in the boreholes at Fenton Hill (GT-2B/EE-1) are limited to 200°C and 28.0 MPa (4000 psi). In addition, testing sondes in the boreholes requires the use of the armored instrumentation cable, which subtracts from the limited life of such a cable in the hostile environment. Access to the boreholes at Fenton Hill is limited because of scheduled flow tests through the energy extraction system for extended periods.

A sonde test stand has therefore been designed and fabricated to check out subassemblies and downhole sondes under conditions simulating deep geothermal wellbores. This test stand will allow more efficient development and testing of downhole tools, cables, and related components. Consequent improvements in the reliability of the tools in the geothermal boreholes can be expected (LASL HDR Project Staff, 1978).

The design criteria for the test facility included a test chamber that will accept borehole sondes up to 152-mm (6-in.) diam and 8.5-m (28-ft) long. The chamber will be temperature-controlled up to 275°C and the fluid (water) pressure controlled up to 41.4 MPa (6000 psi). The chamber will reach the maximum operating temperature 275°C in less than 2 h starting from ambient. It must also be capable of cooling down to a temperature below 90°C from 275°C in less than 2 h. The pressure vessel is a 9.14-m (30-ft) long, 19.4-cm (7-5/8-in.) outside diameter, 15-mm (0.59-in.) wall (API), A-110 tube, 861 MPa (125,000 psi) ultimate and 760 MPa (110,000 psi) yield with buttress-threaded end plates of AISI 4340 steel. It was designed according to ASME VIII Division 2 for 41.4 MPa (6000 psi) and 275°C to 300°C service with water. All of the high-pressure tubing is Autoclave Engineers' "medium pressure tubing" with a minimum working pressure of 138 MPa (20,000 psi) at 38°C and 117 MPa (17,000 psi) at 315°C. All associated valves and fittings are similarly rated.

A block diagram of the test stand is shown in Figure 11. The heater assembly and pressure vessel is inserted in the cm (42-in.) diam CMP housing grouted into the 1.22-m (4-ft) diam drilled hole. The heater assembly and pressure vessel may be removed from the housing with the overhead 5-ton hoist for inspection and repair if necessary. The instrument and control trailer houses an HP 3050B data acquisition system along with ample signal conditioning electronics to monitor up to 20 instrument sonde parameters as well as all necessary monitor and control systems for operation of the test stand. The test stand is available for all DOE and industrial contractors interested in static testing of downhole instrument sondes in the simulated environment.

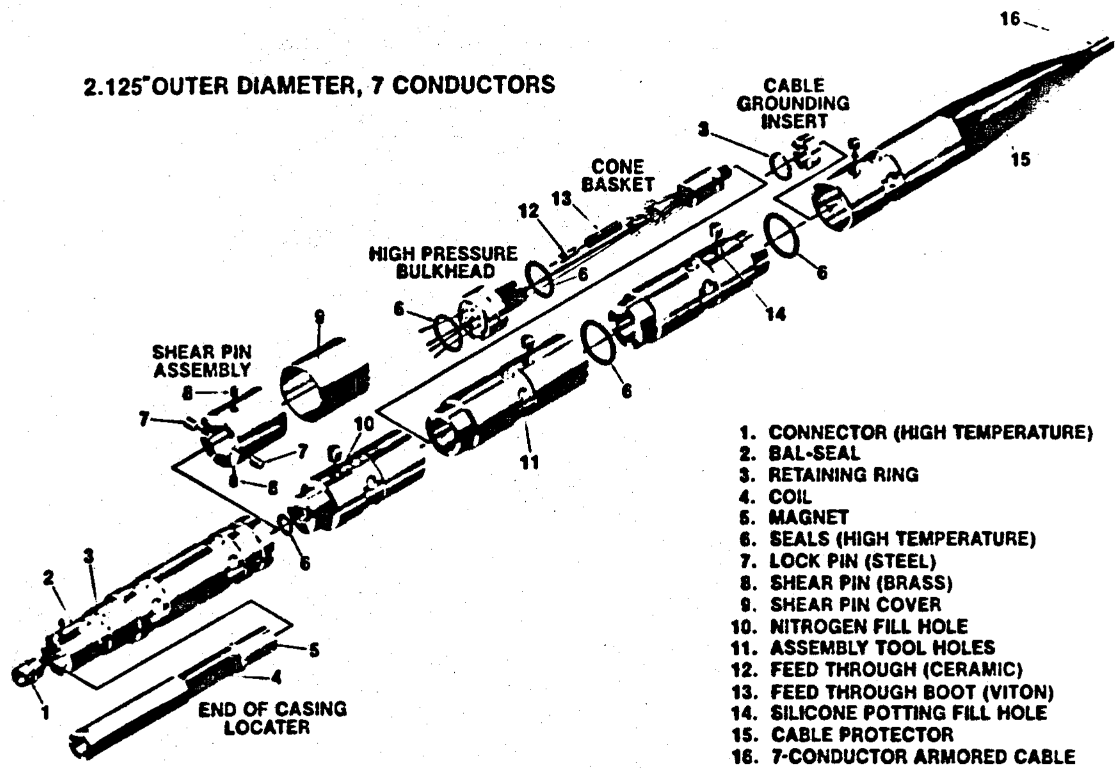

FIG. 1. Cablehead Assembly.

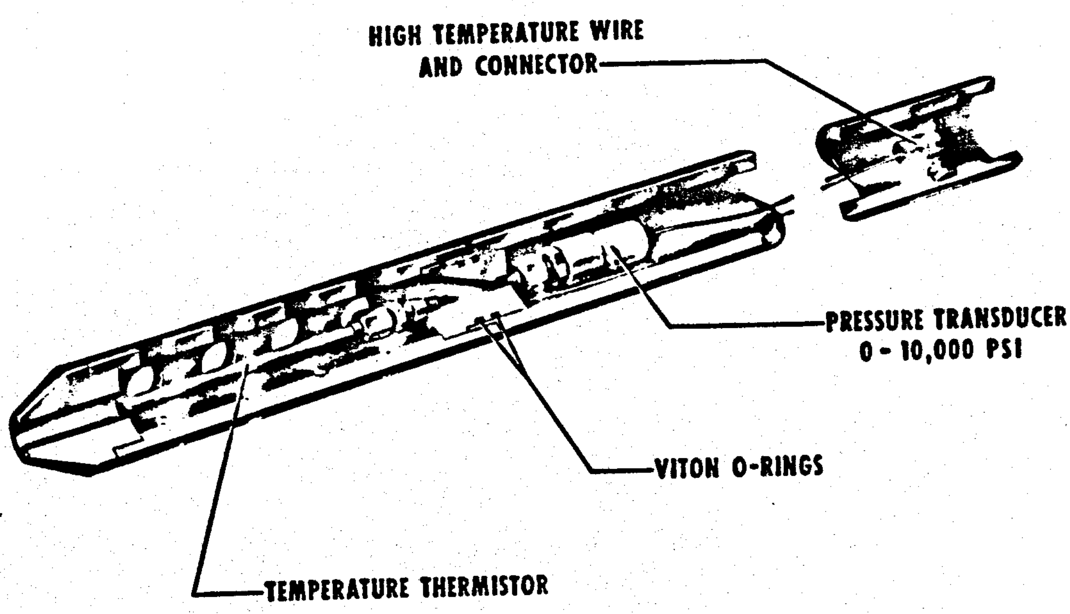

FIG. 2. Pressure and Temperature Probe.

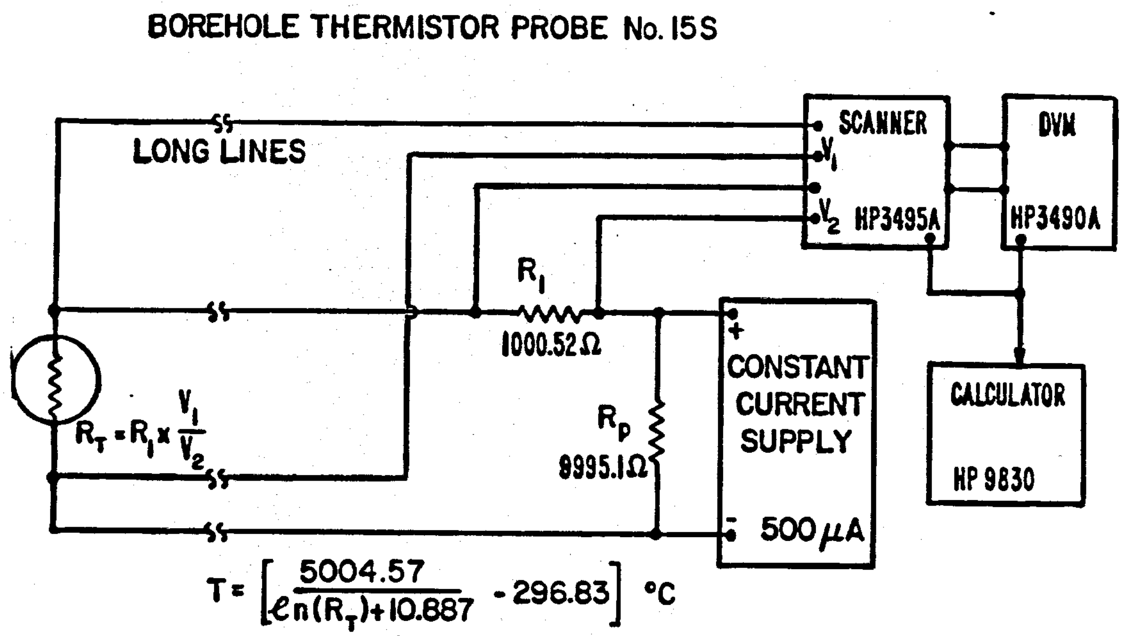

FIG. 3. Schematic Diagram -- Borehole Temperature Measurement.

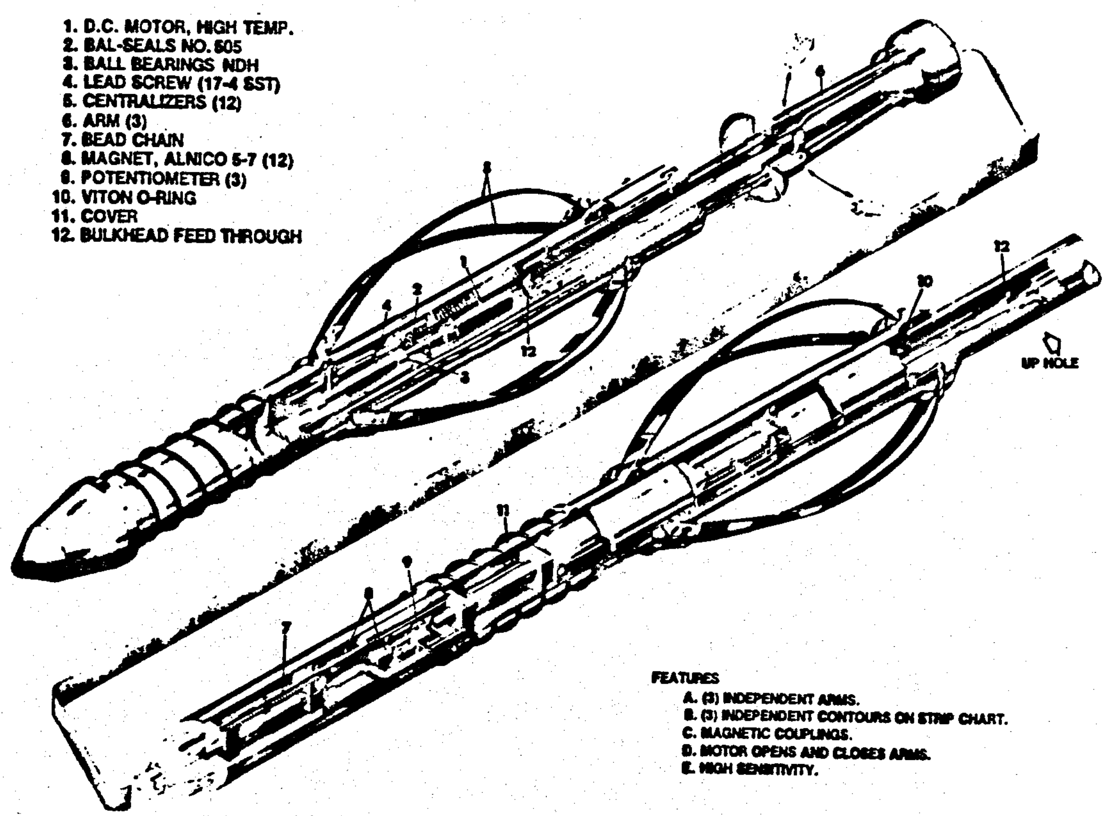

FIG. 4. Caliper and Contour Tool.

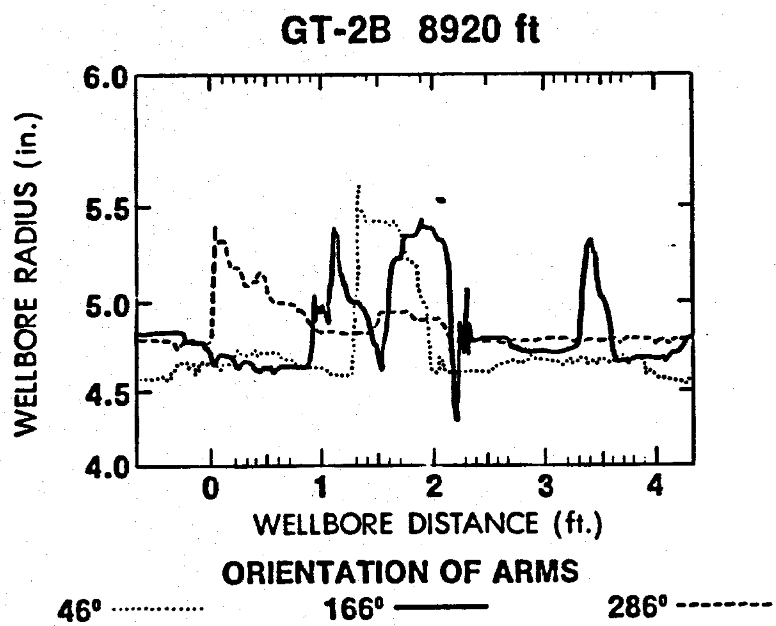

FIG. 5. Caliper Data.

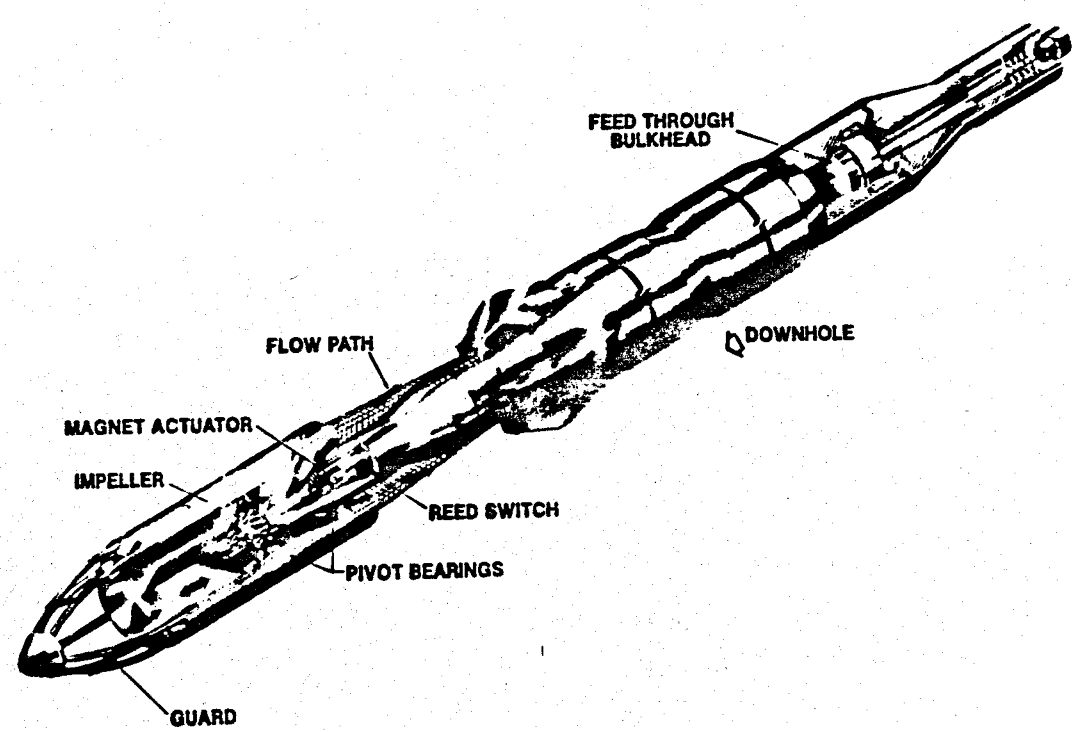

FIG. 6. Fluid Velocity Spinner Probe.

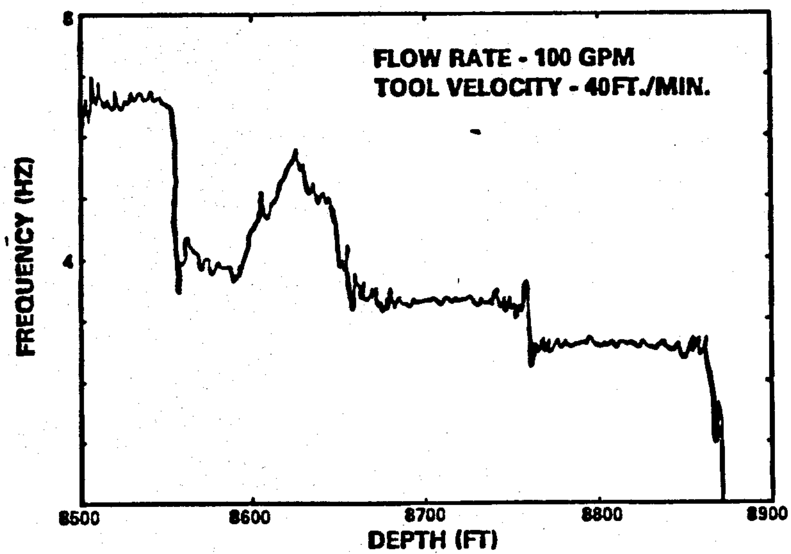

FIG. 7. Spinner Data.

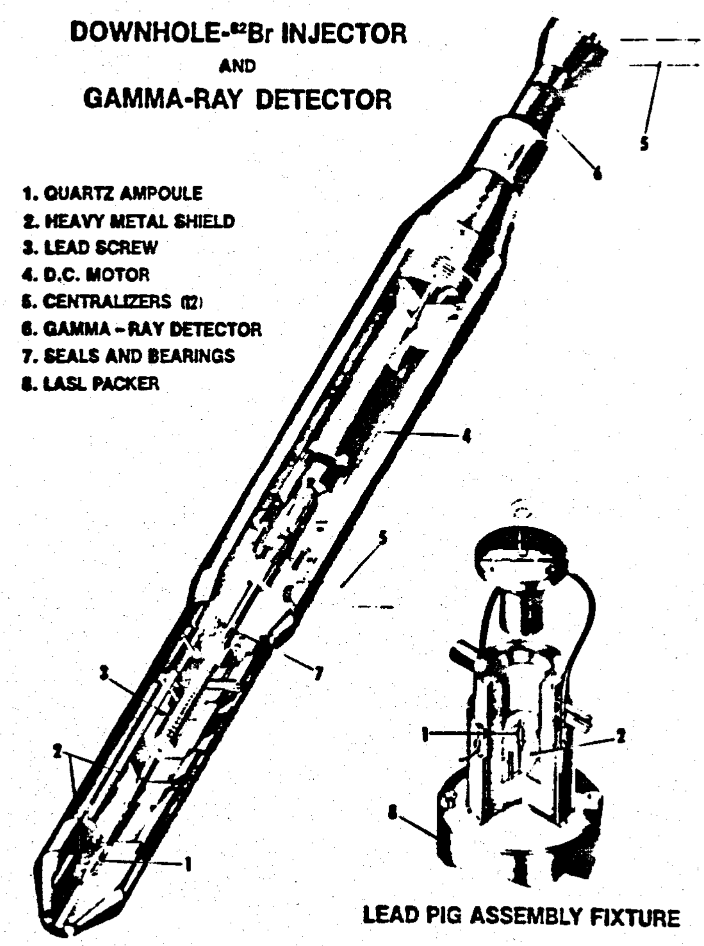

FIG. 8. Downhole-^{82}Br Injector and Gamma-Ray Detector with Lead Pig Assembly Fixture.

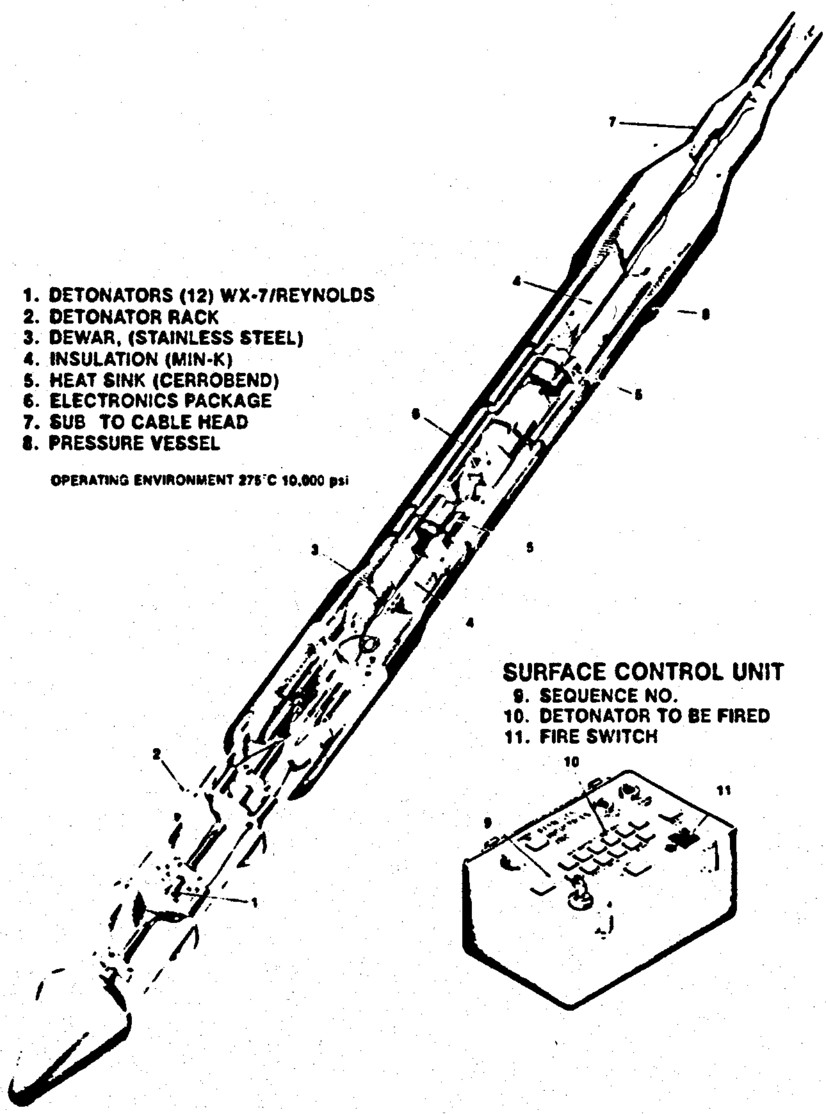

FIG. 9. Acoustic Source Detonator.

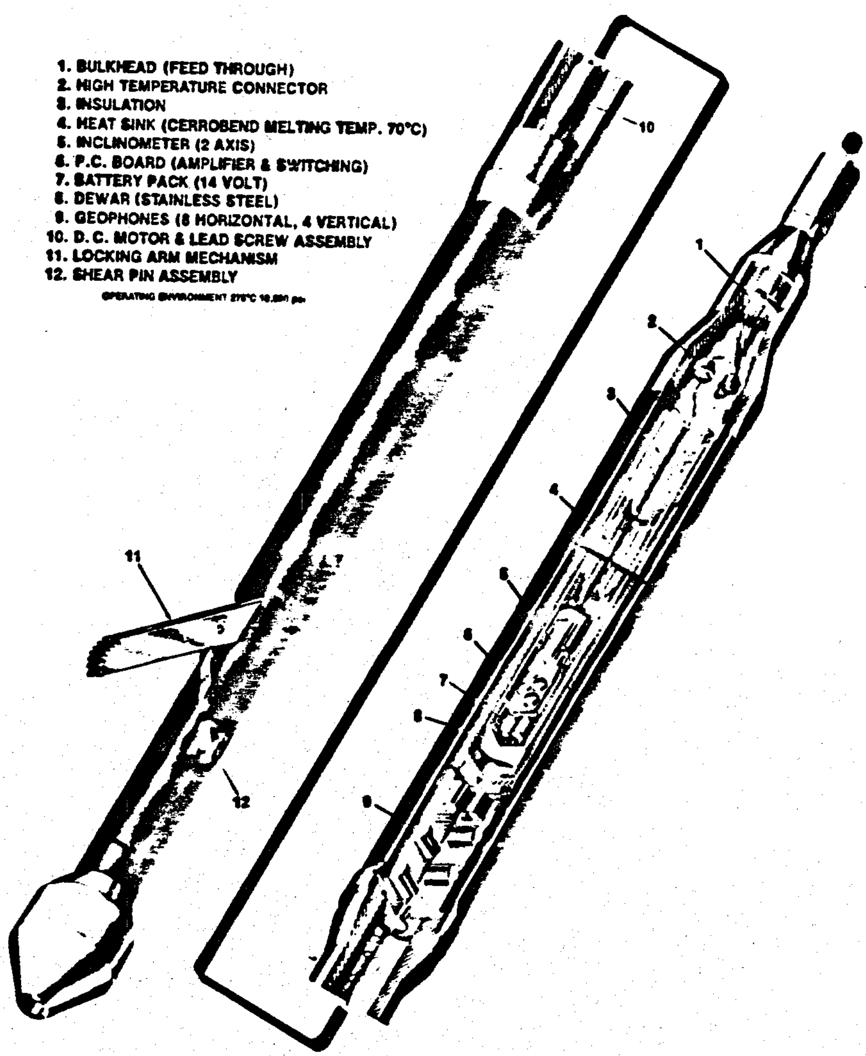

FIG. 10. Geophone Acoustic Detonator.

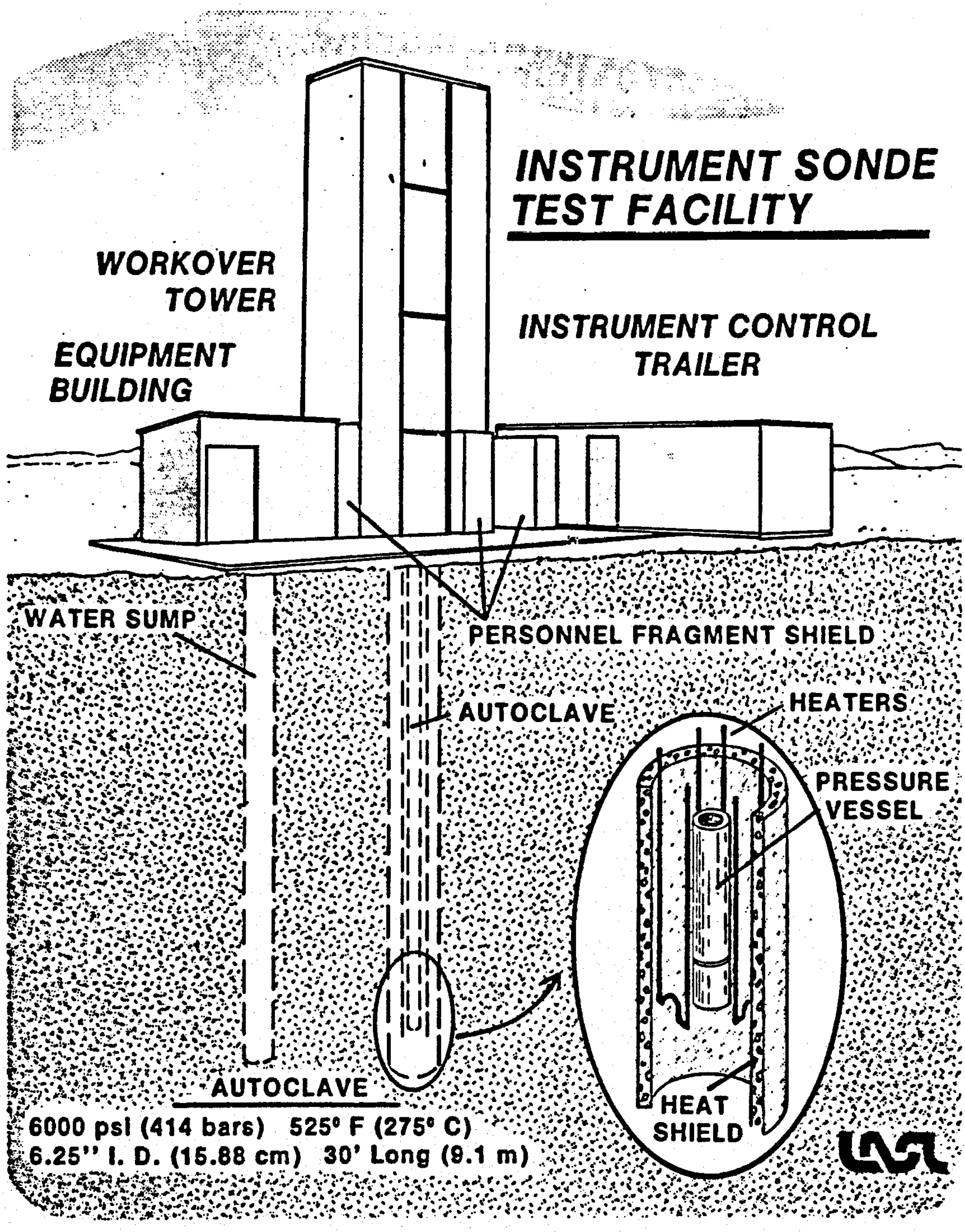

FIG. 11. Instrument Sonde Test Facility.

REFERENCES

Archuleta, J. R. and B. E. Todd, 1978: "Equipment Development Report, High-Temperature Cable Head Assembly," Los Alamos Scientific Laboratory report LA-7325-MS.

Tester, J. W. and J. N. Albright, 1979: "Hot Dry Rock Energy Extraction Field Test, 75 Days of Operation of a Prototype Reservoir at Fenton Hill," Los Alamos Scientific Laboratory report LA-7771-MS.

HDR Program Staff, 1979: "Hot Dry Rock Geothermal Energy Development Program, Annual Report Fiscal Year 1978," Los Alamos Scientific Laboratory report LA-7807-HDR, pp 89-99.

Patterson, W. W., D. R. Deam, H. J. MacDonald, and R. H. Rochester, 1979: "Capacitive Discharge Firing System for Providing Acoustic Sources in the Hot Dry Rock Geothermal Energy Development Project," Los Alamos Scientific Laboratory report LA-7761-MS.

Dennis, B. R., J. H. Hill, E. L. Stephani, and B. E. Todd, 1976: "Development of High-Temperature Acoustic Instrumentation for Characterization of Hydraulic Fractures in Dry Hot Rock," 22nd International Instrumentation Symposium, May 25-27, 1980, San Diego, California.

LASL HDR Project Staff, 1978: "Hot Dry Rock Geothermal Energy Development Project, Annual Report Fiscal Year 1977," Los Alamos Scientific Laboratory report LA-7109-PR, pp 59-60.

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