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A THERMOPILE PROBE TO MEASURE TEMPERATURE ANOMALIES IN GEOTHERMAL BOREHOLES

by

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ABSTRACT

The standard thermal well logging tools presently employed by oil well logging service companies use a thermistor probe as the temperature measuring device. The thermistor is normally incorporated as one arm of a Wheatstone bridge circuit. The bridge circuit must be staged for limited temperature ranges and is adequate for most well logging operations where only detection of thermal anomalies is of primary concern and the logging speed is not important.

The design of a thermopile sensor using conventional thermocouples and a downhole thermally isolated reference junction has greatly improved the temperature logging capability in a deep geothermal wellbore. The much faster response of the thermopile sensor will allow a logging rate of up to 200 ft/min in contrast to the average rate of 50 ft/min using the thermistor probe. The thermopile sensor is a low impedance device whose characteristics are very well known.

The development of a high pressure dewar chamber for use in high temperature downhole instrumentation sondes has provided a suitable environment to employ a downhole reference junction permitting the use of thermocouple measurements in the deep geothermal borehole.

I. INTRODUCTION

At sufficient depth, rock hot enough to be potentially useful as an energy source exists everywhere. In many places, hot dry rock is at depths shallow enough to be reached at moderate cost with existing drilling equipment. 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 hot dry rock at moderate depths.[1] 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.[2] 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 for many years.

On the basis of extensive studies and field experiments, the "Fenton Hill" site was selected for the development of the first hot dry rock energy experiment. This site is located about 32 km west of Los Alamos on the Jemez Plateau in that part of the Rocky Mountains extending into northern New Mexico. As a result of relatively recent volcanic activity, a large amount of heat is still retained in the rock underlying the area within a few kilometers of the surface. The primary objective of the hot dry rock geothermal energy extraction experiment is to investigate and demonstrate the techniques of drilling into the hot granitic rock, fracturing it by hydraulic pressure, producing a connected circulation loop, and then circulating water to extract the heat and transport it to the surface. The field studies 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. A 10 MW thermal energy extraction demonstration is planned as the first milestone for the hot dry rock geothermal program (Fig. 1).

II. DRILLING AND TESTING IN HOT DRY GRANITE

The first exploratory borehole drilled at the Fenton Hill site was designated Geothermal Test Hole No. 2 (GT-2). The Precambrian granitic surface was

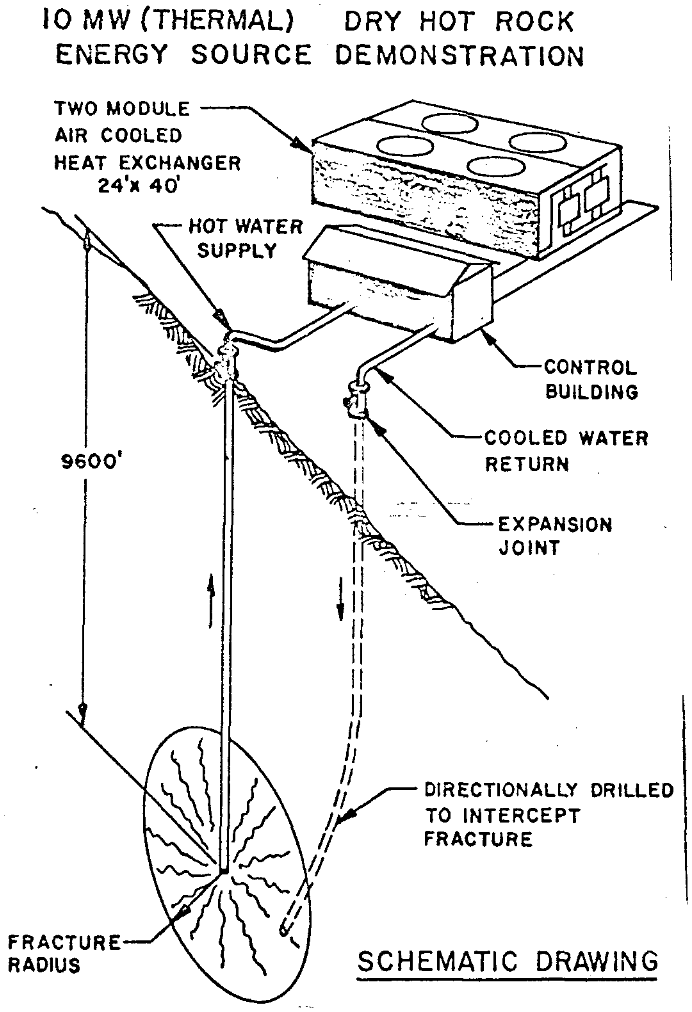

Fig. 1.
Hot Dry Rock Geothermal Energy Extraction Demonstration.

reached at a depth of 733 m (2404 ft).[3] Drilling continued in the granitic basement rock to a depth of 2042 m (6700 ft). Following this 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. Various diagnostic logging operations were performed by well-logging service companies during this drilling and testing phase.[4] LASL instrumentation was developed to measure rock breakdown and fracture extension pressure in the borehole where the bottom-hole temperature at this depth reached 145°C.

Upon completion of the series of experiments at this intermediate depth, the borehole was drilled to a final depth of 2932 m (9619 ft) where the bottom-hole temperature reached 197°C. Again, various diagnostic logging operations were performed by the well-logging service companies. Many problems with equipment failures were experienced in the borehole due to the high temperature environment. A liner was cemented in the open borehole between 2735 m (8973 ft) and 2920 m (9581 ft) to facilitate hydraulic fracture experiments.[6] A polished bore recepticle was installed at the top of the liner to accept 10.3-cm (4-in.) diam tubing run to the surface. The liner was subsequently perforated to perform additional hydraulic fracture experiments in this region of the borehole.

Following a series of pressurization experiments to determine the permeability of the rock at the bottom of the GT-2 borehole, a small hydraulic fracture was formed. A series of hydraulic-fracture extension and pumping experiments were conducted to determine principal tectonic stress, stress variations, and the leak-off rate of the fracturing fluid. Measurements were performed to characterize the fracture and determine stability of the pressurized fracture system. The fracture at the bottom of GT-2 was eventually extended to a radius of 120 m (400 ft). It was important to obtain the dimensions and orientation of this fracture system to achieve intersection of the fracture with the second borehole. Mapping the fracture reservoir was also important to develop an understanding of the flow and heat-transfer properties.

Drilling began on the first energy extraction borehole (EE-1) approximately two months following the completion of GT-2. It was drilled to a depth of 3064 m (10,053 ft) and a measured bottom-hole temperature of 205.5°C. The downhole circulation loop was completed when directional drilling techniques were used to turn the EE-1 borehole to intercept the fracture system. The EE-1 borehole was cased to a depth of 2926 m (9600 ft) with 19.4-cm (7-5/8-in.) diam casing cemented at the bottom.

III. BOREHOLE TEMPERATURE MEASUREMENTS

The drilling program for GT-2 allowed for extensive coring in the Precambrian granitic rock followed by <u>in situ</u> temperature measurements. It was important to minimize the time interval required to extrapolate to an accurate bottomhole temperature.[5] A continuous temperature log of the entire borehole was also necessary to detect geological anomalies such as the presence of aquifers in the granite zones that were communicating with water-bearing zones in the overlying Madera Limestone Formation. Borehole temperature measurements are now used for measuring major departures from previous temperature logs due to hydraulic fracturing and flow experiments in both boreholes. Temperature logs are presently run in the open-hole sections of both EE-1 and GT-2 during pressurization and flow experiments to determine the locations of fluid paths entering and leaving the fracture system.

IV. THERMISTOR PROBES

The initial probes used by LASL for measuring borehole temperatures employed thermistors for the sensing device. The thermistor is essentially a semiconductor that behaves as a temperature-sensitive electrical resistance which provides a high degree of resolution not available in other transducers. They are well suited for measurements exceeding 300°C. The resistance-temperature response is, however, quite nonlinear and varies somewhat from one type of thermistor to another. Each temperature probe, therefore, must be carefully calibrated.

The temperature measurements using the thermistor probes in the GT-2 and EE-1 boreholes employed two recording systems. To obtain accurate bottom-hole thermal measurements, the thermistor resistance was measured with a digital ohms converter having a six digit readout with an accuracy of ±0.02% of full scale. Corrections were made for line resistance, measured as the sonde was lowered in the borehole, to compensate for thermal effects on the cable. The resistance data were converted to temperatures using a linearization equation computed for each probe (Fig. 2). To log the borehole continuously on a strip chart recorder, the thermistor was employed in one arm of a wheatstone bridge network. The resistance span of the bridge was chosen to minimize the nonlinear characteristics of the thermistor. To maintain an accuracy of less than 4%, the temperature intervals were restricted to ranges of 50°C (Fig. 3). For logging the cooler regions of the borehole, the thermistor resistance was quite high (575 kΩ at 80°C for the nominal 10 MΩ thermistor and 66 kΩ at 80°C for the nominal 1 MΩ thermistor).

The bridge network presented a high impedance to the recording equipment. This high impedance of the source resulted in poor signal-to-noise ratio and decreased the resolution of the measuring system. The temperature sensors were Fenwal thermistor glass beads (Type GA-61P8 and GA-71P8). These glass-coated thermistors were evaluated for their stability characteristics and proved to have the best stability properties over a useful temperature range up to 316°C. The thermistor sensors were temperature cycled to improve stabilization prior to assembly in the temperature probe. The thermistor leads were Durmet wires and were silver soldered to #22 AWG Teflon insulated lead wires. The thermistor

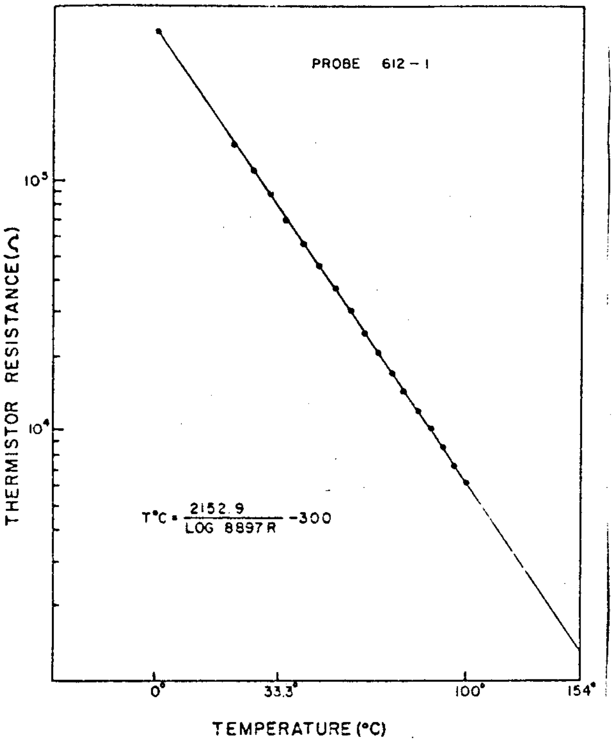

Fig. 2.
Thermistor probe linearization.

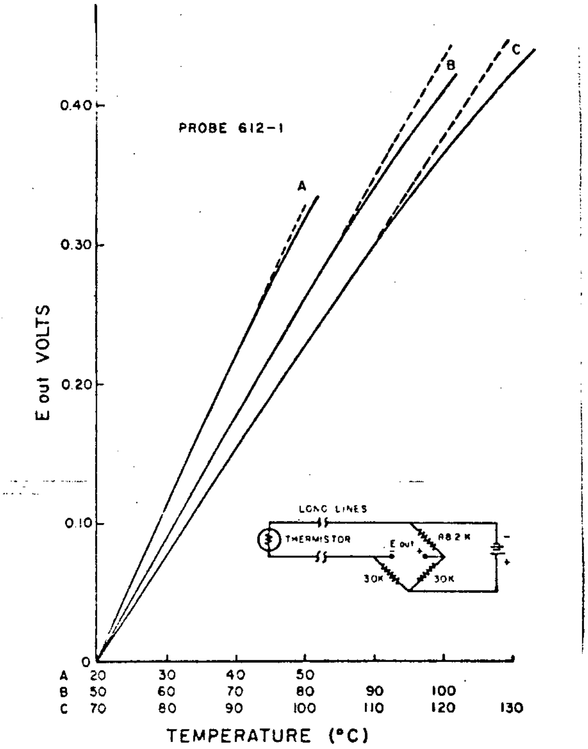

Fig. 3.
Thermistor probe bridge network calibbration.

probe was then forced into contact with a copper plug that was silver brazed into the end of a stainless steel tube employed as a protective sheath. The stainless sheath, 188-mm (7-in.) long and 7.94-mm (0.312-in.) o.d. by 6.16-mm (0.242-in.) i.d., was pressure tested for an equivalent depth of 4230 m (13,880 ft) of water or 414.2 bars (6000 psi). The void volume within the sheath was filled with technical "G" copper cement up to a level of 25 mm (1 in.) below the open end of the sheath. This cement will withstand temperatures up to 500°C and provides a thermally conducting electrical insulation. After the cement cured, the remaining void section at the top of the sheath was filled with Dow Corning 92-024 high temperature aerospace sealant. The total mass of the probe was about 49 g (1.73 ounces).

The thermistor probe was assembled in a downhole sonde for logging operations. A perforated cage was incorporated into the leading end of the sonde to protect the probe from damage while descending the borehole. A block diagram of the probe is shown in Fig. 4.

The time constant* of the thermistor probe assembled in the downhole sonde was measured to be 7.63 s for a logging rate of descent of 7.62 m/min (25 ft/min). The indicated temperature lag from the true fluid temperature in the borehole would be 0.058°C (ambient temperature of 200°C). The time constant of this probe would be 7.54 s at a logging rate of 10.7 m/min (35 ft/min) corresponding to a temperature lag of 0.080°C.

V. THERMOPILE PROBE

To improve the borehole temperature measurements at increased logging rates, LASL developed a borehole thermopile transducer. The thermopile was constructed by wiring seven chromel-alumel thermocouples in series. Each ungrounded thermocouple was sheathed with 304 stainless steel tubing filled with magnesium oxide insulation. The 1.59-mm (0.0625-in.) diam sheath had a wall thickness of 0.254-mm (0.01-in.). The cold junctions were submersed in an ice bath. The ice bath was provided by an ice filled dewar housed in a sealed pressure shell (Fig. 5).

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*Time required to reach 63% of an instantaneous temperature change.

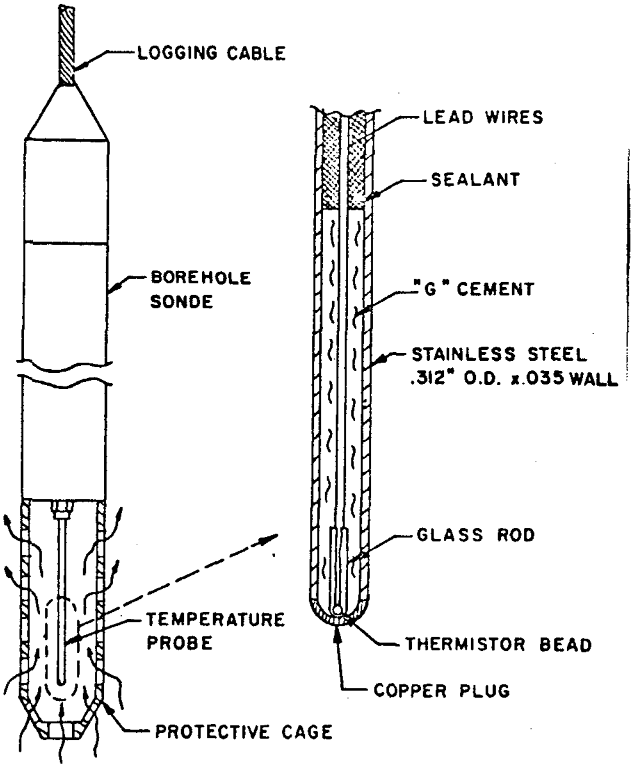

Fig. 4.
Borehole thermistor temperature sonde.

Fig. 5.
Borehole thermopile temperature sonde.

A second thermocouple was set in the dewar to measure the ice bath temperature. The reference for this second thermocouple was provided by a self-compensating electrical bridge reference junction (Consolidated Ohmic Model JR114APOC) that was also submersed in the ice bath. The reference junction was tested in an oven to insure 0°C compensation up to temperatures exceeding 80°C. This would allow measurements in the borehole after the ice had melted. The dewar, filled with crushed ice, would maintain an internal temperature of 0°C for 6 h when the downhole sonde was subjected to a borehole temperature of 200°C.

The time constant for the thermopile was measured for comparison with the thermistor probe. For a logging rate of 7.62 m/min (25 ft/min) the temperature lag was 0.002°C with a time constant of 0.310 s. A comparison of response for the thermopile and thermistor is summarized in Table I. The thermocouple characteristics are well known, and when calibrated the accuracy is greater than 0.1%. The thermopile presented a low source impedance to the surface readout equipment. Figure 6 compares the temperature readout of the thermopile at logging rates of 25 ft/min and 80 ft/min. The temperature anomalies shown in the figure are explained later in the text.

VI. SUMMARY OF FIELD MEASUREMENTS

Temperature measurements were made throughout the Precambrian granitic rock section of GT-2 during the drilling phase. Several techniques were developed to

TEMPERATURE PROBE

WITH DEWAR AND THERMOPILE

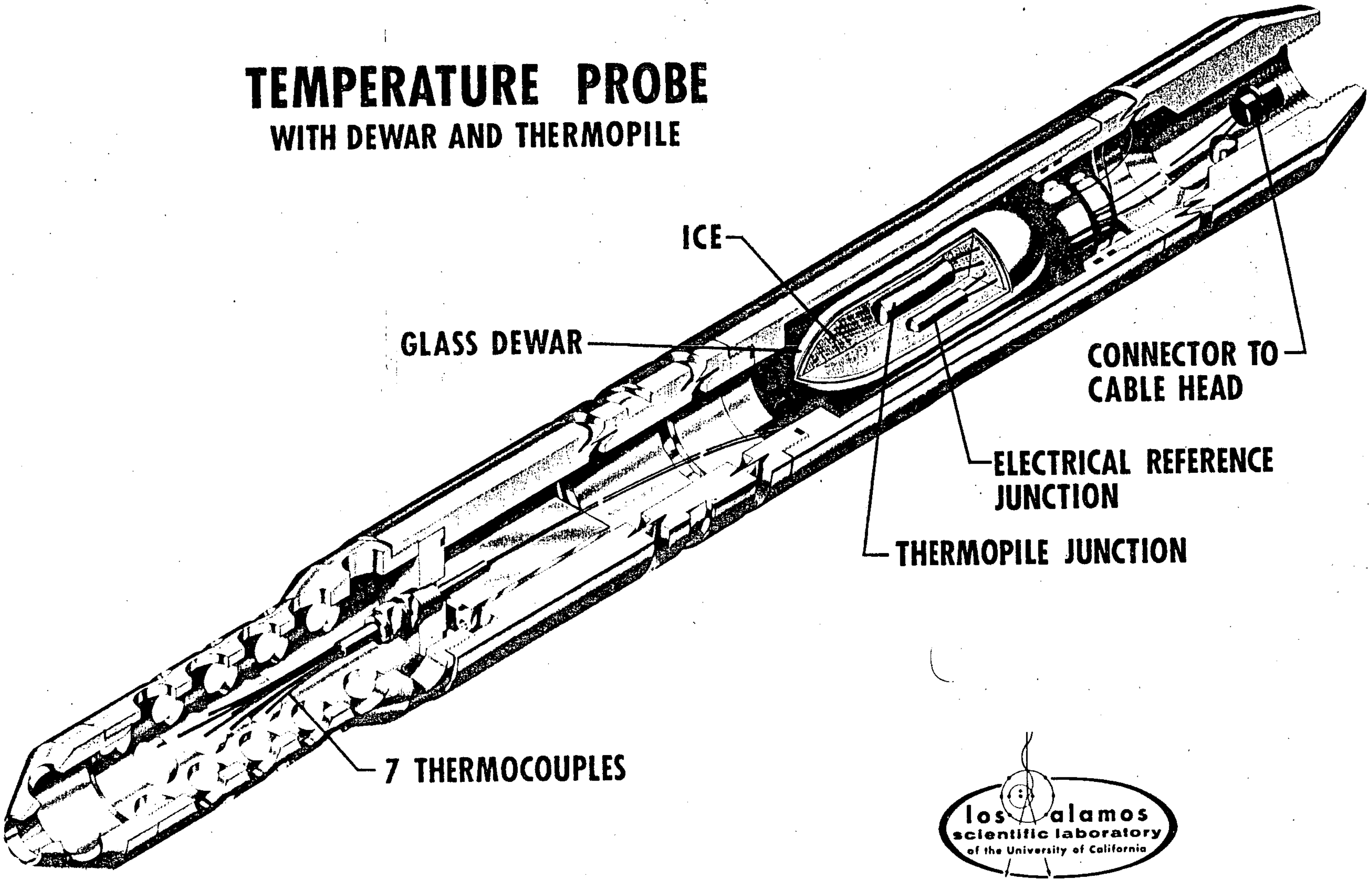

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TABLE I

M/Min	Ft/Min	Thermistor $\Delta\tau^a$	Thermistor ΔT^b	Thermopile $\Delta\tau^a$	Thermopile ΔT^b
7.62	25	7.63	0.058	0.310	0.0020
10.70	35	7.54	0.080		
24.38	80	7.33	0.179	0.165	0.0034

$^a\Delta\tau$ = time constant of probe in seconds

$^b\Delta T$ = temperature lag (true-indicated) °C

to insure accurate bottom-hole temperatures in the fluid filled borehole.[5] Equilibrium rock temperatures calculated from relaxation data show geothermal gradients approaching 60°C/km. The extrapolated equilibrium rock temperature at the terminal depth of 2932 m (9619 ft) was 197°C in GT-2.

Bottom-hole temperature measurements were made at less frequent intervals during the drilling of EE-1 since the thermal gradient had been well established. The extrapolated equilibrium rock temperatures at the terminal depth of 3064 m (10,053 ft) in EE-1 was 205.5°C.

Prior to initiation of the hydraulic fracture experiments and extensive flow tests, a background temperature log was run in each borehole. These temperature measurements established a base gradient from which the effects of the hydraulic fractures and flow test could be determined. The background temperature measurements are shown in Fig. 7. The sudden change in the temperature gradient at 731.5 m (2400 ft) occurs where the Precambrian granite begins. Temperature logs were made in both EE-1 and GT-2 during the large number of flow tests which were conducted to characterize the fracture system connecting the two boreholes. Only the results of the temperature logs will be presented here.

Figure 8 describes the temperature logs run during an early low pressure flow experiment with the surface pressure not exceeding 34.45 bars (500 psi). The flow during this experiment was initiated in GT-2. The temperature anomalies measured in the borehole in the interval 2800 m (9186 ft) to 2850 m (9350 ft) and in the interval 2880 m (9448 ft) to 2920 m (9580 ft) show major departures from the original temperature log of GT-2. The background log prior to pumping shows

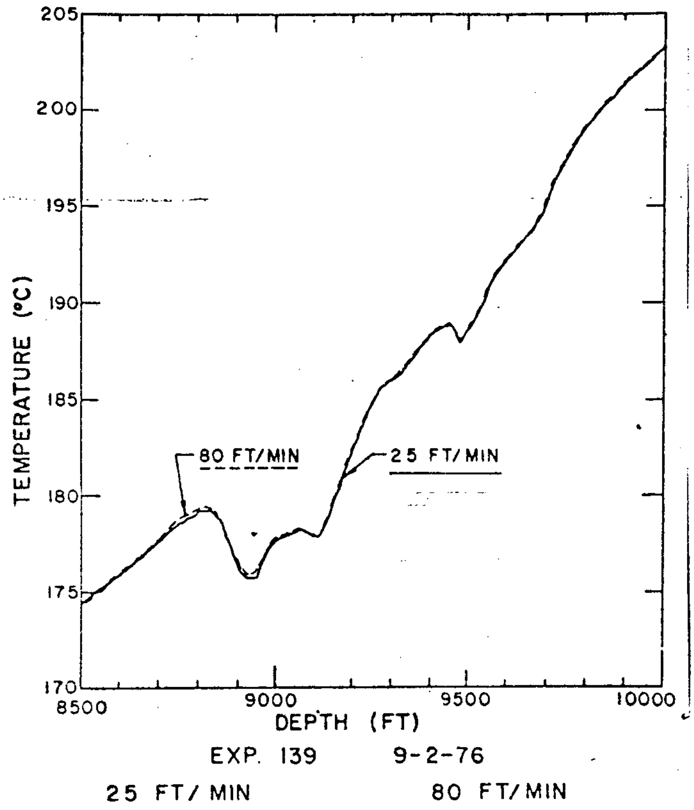

Fig. 6.
Thermopile response vs logging speeds.

the long term result of previous hydraulic fracturing and pressurization experiments where large quantities of cold water were forced into the fractured regions. Analysis of the time-temperature data obtained during the pumping phase indicates that 80% of the fluid leaves the borehole at the 2820-m (9200-ft) interval and 15% leaves at the 2880-m (9448-ft) interval with the rest leaving at the bottom of the borehole (see Appendix A).

A pressurization experiment in the EE-1 wellbore was run to determine the intersection of the fracture system with this borehole. The surface pressure was increased to 93.7 bars (1360 psi) during the pumping phase to insure fracture inflation. The background log made prior to pumping recorded no anomalies. The log made during the flow phase showed that the fluid was leaving the borehole in the interval from 2941 m (9650 ft) to 2957 m (9700 ft) (Fig. 9).

An important consequence of the analysis of the flow experiment data proved that the impedance to flow from the wellbores through the fracture system was too high to establish a meaningful thermal energy extraction demonstration. Plans were made to improve the wellbore impedance by employing chemical leaching

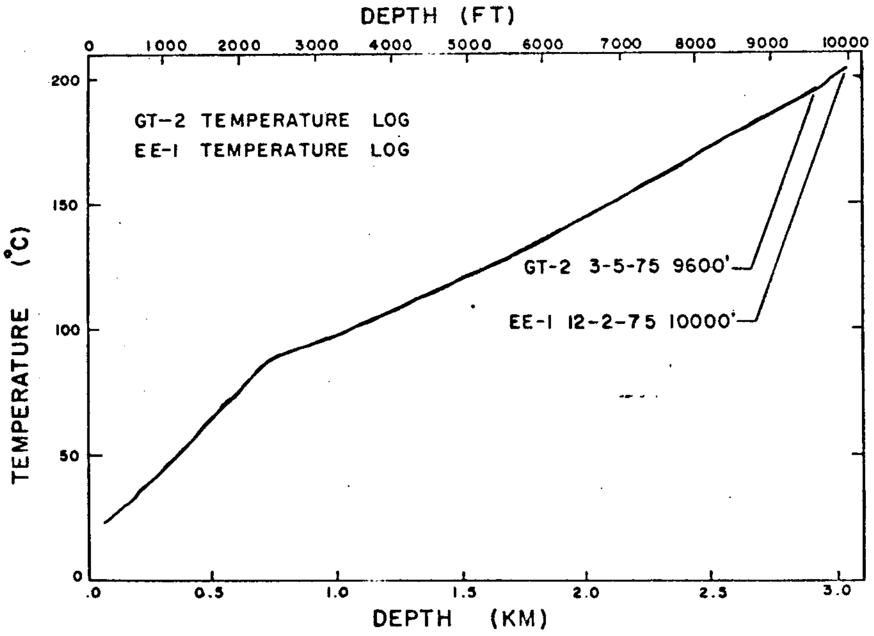

Fig. 7.
GT-2/EE-1 borehole background temperature logs.

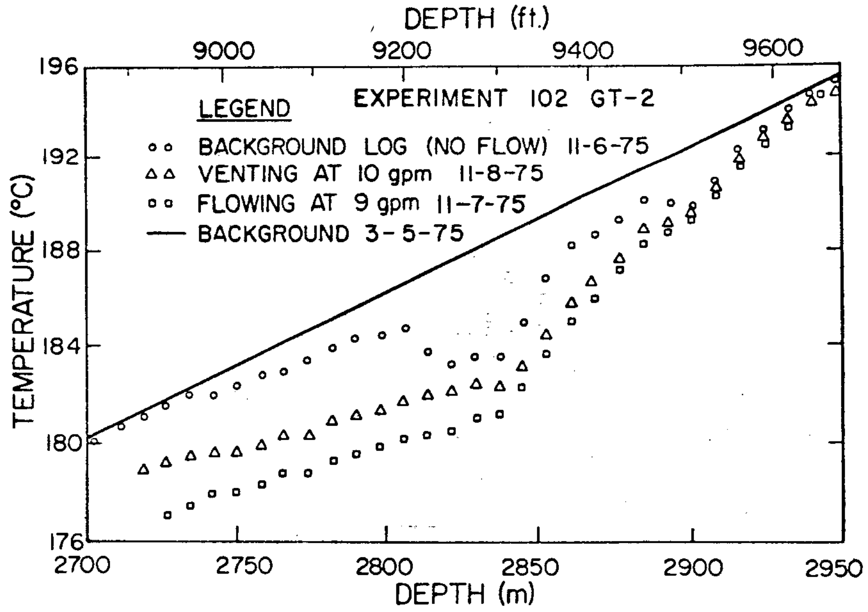

Fig. 8.
Temperature logs during low pressure flow experiment GT-2.

techniques. A pre-leach flow experiment was conducted to record the existing fracture system parameters for comparison purposes. Prior to that start of pumping, background temperature logs were made in both GT-2 and EE-1 from a depth of 2600 m (8500 ft) to the bottom of each borehole (Fig. 10). The strange anamolies that were measured in the EE-1 borehole at this time were of concern. Later temperature logs repeated over this interval confirmed the erratic behavior of the fluid temperature and indicated that the cement bond between the wellbore and the casing had deteriorated for several hundred feet up the borehole and the fluid was circulating behind the casing in this region. During the pumping phase of this experiment, a sudden drop in the GT-2 shut-in pressure accompanied by a large increase in the GT-2 annulus flow rate indicated that the fracture system had suddenly broken through into the GT-2 borehole above the cemented liner. The point of entrance of the fluid into the annulus would appear as a temperature anomally. The post flow temperature log plotted in Fig. 11 did show a sudden rise in temperature at 2770 m (9100 ft).

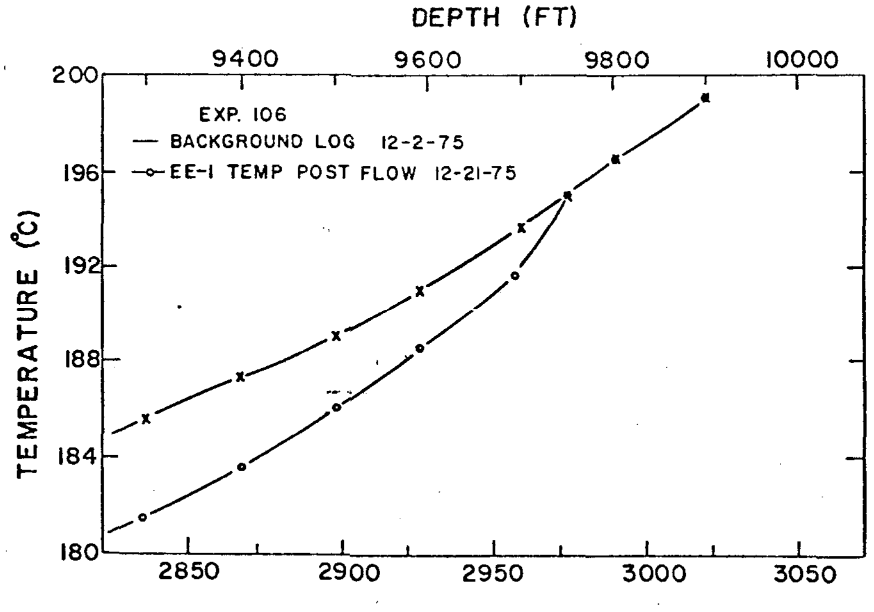

Fig. 9.
Temperature log during high pressure flow experiment EE-1.

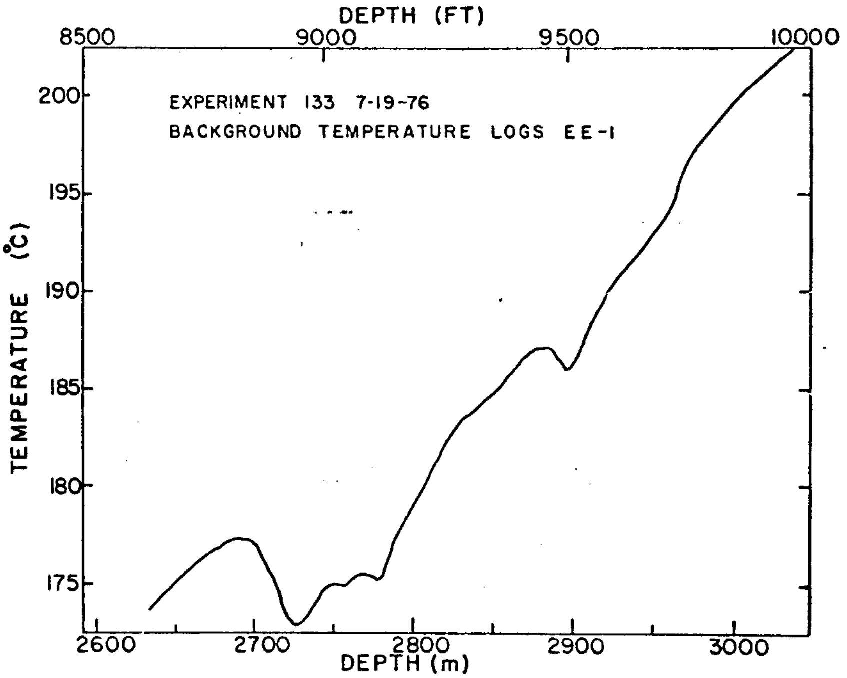

Fig. 10.
Pre-leach temperature log EE-1.

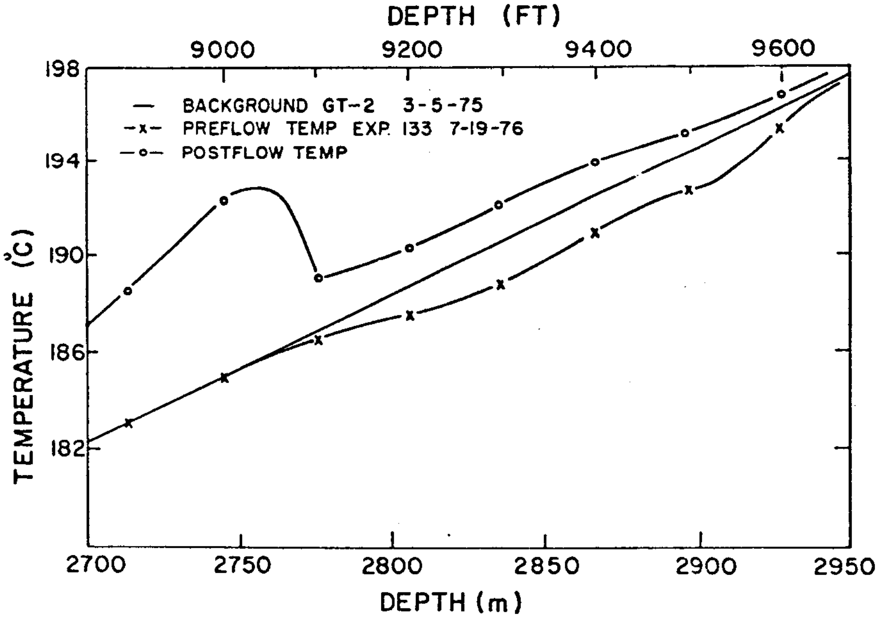

Fig. 11.
Pre-leach temperature log GT-2.

VII. CONCLUSION

The temperature probe is one of the less complex logging tools and is readily fielded allowing quick data acquisition for easy analysis. The temperature measurements in the geothermal boreholes have proven to be most valuable in determining the changing conditions of the fracture system. The analysis of temperature anomalies has lead to corrective measures that have prevented major setbacks in proceeding with a 10 MW thermal extraction facility. Procedures have been implemented to re-cement the void behind the EE-1 casing and to improve the wellbore-fracture flow impedance. Specifications to construct the 10 MW thermal circulation loop are complete and fabrication has begun.

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APPENDIX A

If the assumptions are made that the properties of the rock material surrounding the wellbore and the wellbore geometry are constant, then a relationship can be derived to describe the ratio of fluid velocities in the wellbore at different depths Z. By assuming constant rock properties and a constant wellbore radius, the ratio of water velocity U_2, at some depth Z_2 and time t to the velocity U_1, at a reference depth, Z_1, is related to the water temperature changes and water temperature gradients, $\overline{G}$, at these depths and time as

$$\frac{U_2 = T(Z_2) - \mathrm{To}(Z_2)\quad \overline{G}(Z_2)}{U_1 = T(Z_1) - \mathrm{To}(Z_1)\quad \overline{G}(Z_1)}$$

where the gradient $\overline{G}$ is an "effective average"[7] gradient. For short time tests with insignificant wellbore heat storage, a useful approximation for $\overline{G}$ is

$$\overline{G} = \sqrt{G(t)\ 1/t \int_0^t G(\tau)d\tau}$$

The above conditions were satisfied during the flow log of Experiment 102, which started 430 min after initiation. By choosing the reference depth Z_1 = 2790 m, the fluid velocities relative to the velocity at Z = 2790 m were calculated and are plotted in Fig. A-1. Changes in flow rate are clearly identified; about 80% of the flow leaves the wellbore in the interval between 2800 and 2820 m, about 15% leaves at 2870 m, and the rest leaves at the bottom of the hole.

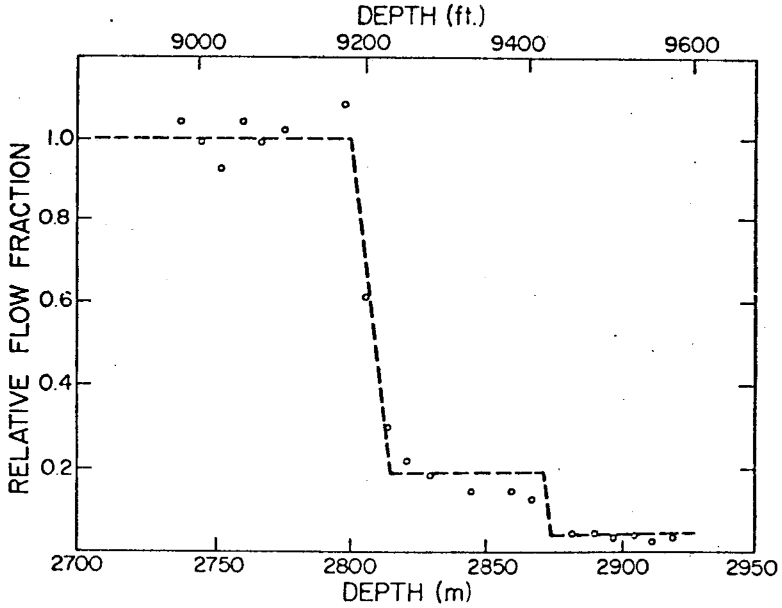

Fig. A-1.
Relative fluid velocities vs wellbore depth.