

TITLE: BOREHOLE TEMPERATURE SURVEY ANALYSIS HOT DRY ROCK
GEOHERMAL RESERVOIR

AUTHOR(S): B. R. Dennis and H. D. Murphy

SUBMITTED TO: The Geothermal Resource Council for its 1978
Annual Meeting to be held at Hilo, Hawaii on July 25-28, 1978.

By acceptance of this article for publication, the publisher recognizes the Government's (license) rights in any copyright and the Government and its authorized representatives have unrestricted right to reproduce in whole or in part said article under any copyright secured by the publisher.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the ~~USERDA~~ DOE.


los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

See

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

BOREHOLE TEMPERATURE SURVEY ANALYSIS
HOT DRY ROCK GEOTHERMAL RESERVOIR

Bert R. Dennis
Hugh D. Murphy

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
LOS ALAMOS, NEW MEXICO 87545

ABSTRACT

The Los Alamos Scientific Laboratory (LASL) has been actively investigating the potential for extracting geothermal energy from hot dry rock. A man-made geothermal reservoir has been formed at the Fenton Hill Test Site in northern New Mexico. The 10-MW (thermal) prototype energy extraction circulation loop has been completed and has been continuously operating since January 28 of this year. The performance of the Phase I 1000-h circulation experiment would establish technological assessment of the particular hot dry rock geothermal reservoir. The major parameters of interest include equipment operations, geochemistry, water loss, and reservoir thermal drawdown.

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 in the hydraulic-fracture system. Several downhole temperature instruments have been designed and fabricated for use in the GT-2/EE-1 wellbores.²

DOWNHOLE TEMPERATURE SURVEY MEASUREMENTS

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 Fig. 1. 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°C to 205°C. The temperature-resistance characteristics are linearized by the function:

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

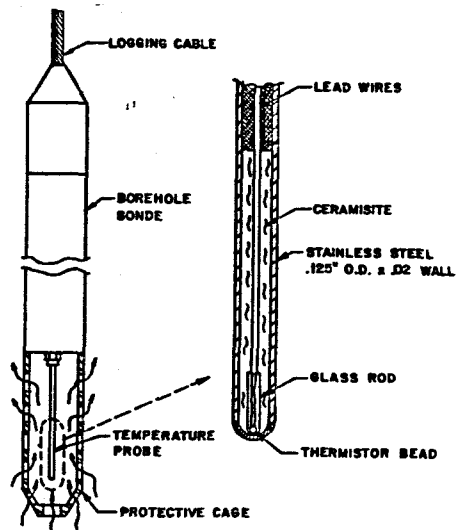


Fig. 1.
Borehole temperature sonde.

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.

For 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 Fig. 2. 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

BOREHOLE THERMISTOR PROBE No. 155

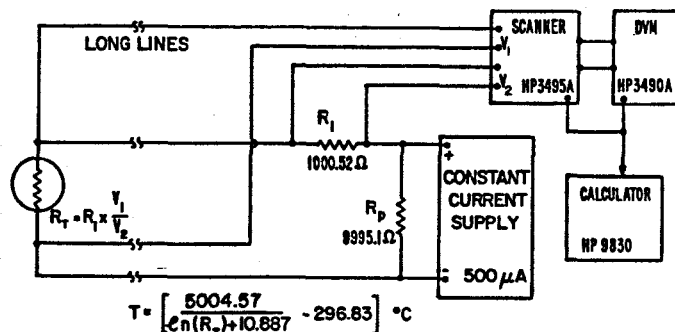


Fig. 2. Schematic diagram of borehole temperature measurement.

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.

EE-1 WELLBORE TEMPERATURE SURVEYS

A review of selected wellbore temperature surveys in EE-1 will be presented. Data obtained during the temperature surveys emphasizes the changing conditions in the borehole where the hydraulic fracture connections intersect the wellbore. Several surveys, identified as background, were made just prior to flow experiments. The experiments were conducted at time intervals spaced to allow thermal recovery from each flow test. Post-flow or post-fluid injection surveys were taken shortly after the experiment in which the temperature anomalies are masked by the cooling effects of the flow tests.

The region of greatest interest in the EE-1 wellbore is from a depth of 2400 m (8000 ft) to 2950 m (9800 ft). The results of the selected surveys are plotted in Fig. 3. The upper curve is a temperature survey taken just a few days after initiating the first hydraulic fracture in EE-1. This survey was taken during an early flow experiment when water was being pumped into GT-2 through the initial reservoir system and up EE-1. The temperature anomaly identified as No. 1 at 2925 m (9590 ft) corresponds with the depth of the bottom of the casing in EE-1 and was assumed to be the top of the fracture intersection in EE-1. The second curve from the top shows a post-flow survey following the EE-1 injection experiment. During this flow test the surface pressure in the EE-1 wellhead reached a level of 100 bars (1450 psi) which exceeded the pressure estimated to initiate new fractures or extend old ones. This survey shows some new anomalies that suggest new connections above the bottom of the cemented casing.

On March 5, 1976, EE-1 was pressurized to 115 bars (1650 psi) at flow rates up to 13.5 L/sec

(5 bbl/min). The third curve is a background log taken several months later clearly showing the results of this high-pressure test where additional fracture to wellbore intersections are evident above the bottom of the cemented casing. It was believed at this time, that the cement between the casing and rock formation had deteriorated several hundred feet up the wellbore due to the high temperatures, thereby allowing water to penetrate through the resulting annulus and into the formation at the depths indicated at these new connections. Deterioration of the cement was confirmed by several cement bond logs and the flow paths were confirmed by an Iodine tracer log.

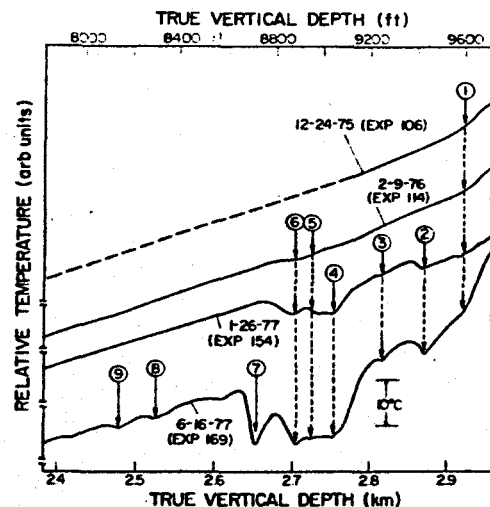


Fig. 3. Temperature surveys EE-1.

Another high-pressure, high-flow rate test was performed in EE-1 prior to redrilling GT-2B. This time the wellhead was pressurized to 128 bars (1850 psi) at a flow rate of 27 l/sec (10 bbl/min). The results of this flow experiment are shown in the bottom curve, plotted from a temperature survey conducted one month later. A new major connection appears at 2650 m (8700 ft) with smaller connections at 2525 m (8290 ft) and 2480 m (8145 ft). This survey also indicates that very little water is flowing into the first EE-1 fracture which may have partially sealed.

IDENTIFICATION OF GT-2B FLOW CONNECTIONS

The high impedance to flow in the EE-1/GT-2 fracture system resulted in a decision to redrill in GT-2. A new path, GT-2B, was targeted at the EE-1 fracture to improve the fracture system connections. The redrilling was successfully completed in May of 1977. To determine the intersections with the GT-2B wellbore and the relative flow paths at these intersections, a number of temperature surveys were made while continuously pumping into GT-2. The results of the surveys are shown in Fig. 4. The upper survey is a background log taken with the borehole shut in (no flow). Two strong anomalies appear at depths of 2700 m (8860 ft) and 2670 m (8755 ft) with a relatively small anomaly at 2640 m (8630 ft). These anomalies are the result of pumping into EE-1 while GT-2 was vented.

In order to determine the relative amounts of water flowing into these connections, the well was surveyed at various times after the start of pumping into GT-2B. In sequence the results of these surveys are presented as the first through the fourth flowing survey. The cooling of the well, as well as, the convective flow-induced dispersion of the anomalies are readily apparent. The ratio of the flow rates at two particular depths, denoted as depths 1 and 2, is given by³

$$\frac{Q_2}{Q_1} = \frac{\Delta T_2 g_{e,1}}{\Delta T_1 g_{e,2}} \frac{\left[\sqrt{1 + \lambda_2^2} - \lambda_2 \right]}{\left[\sqrt{1 + \lambda_1^2} - \lambda_1 \right]} \quad \dots (1)$$

where the effective average gradient is

$$g_e = \sqrt{\bar{g}(t)} g(t)$$

$$\bar{g}(t) = \frac{1}{t} \int_0^t g(\tau) d\tau$$

Temperature gradients are evaluated as $g = \partial T / \partial z$, where T and z are temperature and depth respectively. Flow rates and temperature changes at a particular depth, say z_1 , are denoted as Q_1 and ΔT_1 . The parameter λ is related to the properties of the rock and water. For flow periods of several hours or more it is found that λ is small enough to be neglected.

The temperature results of Fig. 4 were analyzed per eq. (1) and the resulting flow rates, normalized to the surface injected rates are shown in

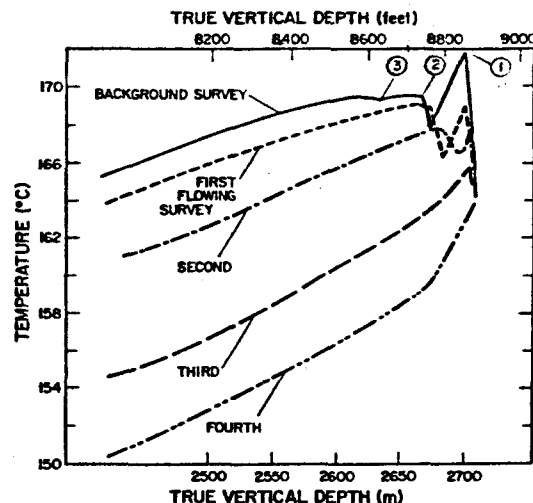


Fig. 4.
Temperature surveys GT-2B.

in Fig. 5. It is apparent that 22% of the pumped flow enters the formation of GT-2B connection 1, 78% at connection 2, and a negligible amount at 3.

TEMPERATURE DRAWDOWN GT-2B

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 cable-head assembly. The cable head was designed and fabricated at LASL specifically for long-term residence in the high-temperature, high-pressure environment (Fig. 6). 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. The temperature sonde and associated cable head met all the performance criteria for a total of 1056 h in the bottom of the borehole.

Several temperature surveys, shown in Fig. 7, were taken during the 1000-h test. The plots show the trend of the reservoir drawdown as well as the various intersections where water is entering the GT-2B wellbore. A large flow path near the bottom of the wellbore results in relatively cool water entering the system. A number of additional intersections show the flow of much hotter fluid. The connection system as shown by this temperature

Dennis

data is now quite complex with the numerous intersections and flow-induced dispersion. To determine the relative amounts of flow through each connection with the wellbore would be very difficult without the additional information that might be obtained with a fluid velocity survey. A fluid velocity survey tool that will survive the geothermal borehole environment has, therefore, become a high priority development program to add to the refinement of the reservoir assessment for the Fenton Hill Hot Dry Rock Geothermal System.

REFERENCES

1. A. G. Blair, J. W. Tester, and J. J. Mortensen, "LASL Hot Dry Rock Geothermal Project, July 1, 1975 - June 30, 1976," Los Alamos Scientific Laboratory report LA-6525-PR, pp 60-83 (October 1976).

2. B. R. Dennis, E. L. Stephani, and B. E. Todd, "A Thermopile Probe to Measure Temperature Anomalies in Geothermal Boreholes," Ninth Transducer Workshop, Ft. Walton Beach, Florida, April 26-28, 1977, Los Alamos Scientific report LA-UR-77-574.

3. H. D. Murphy, "Fluid Injection Profiles - A Modern Analysis of Wellbore Temperature Surveys," Soc. Petroleum Engineers, Paper 6783 presented at 52nd Annual Meeting, Denver, Colorado, October 9-12, 1977.

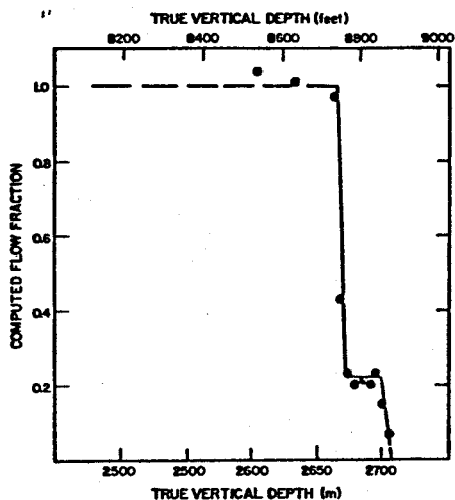


Fig. 5. Flow fraction vs connection GT-2B.

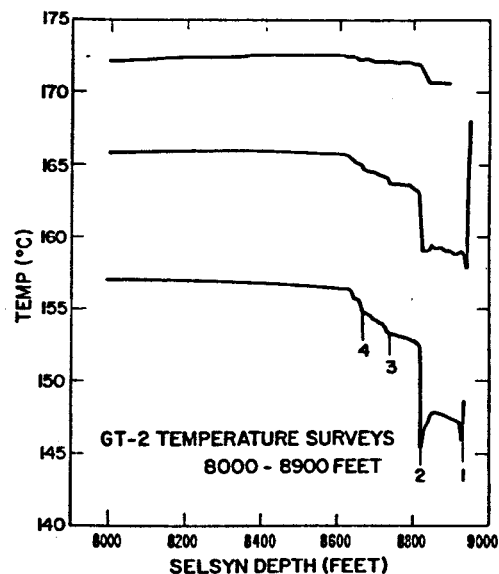


Fig. 7. Temperature survey GT-2B reservoir drawdown.

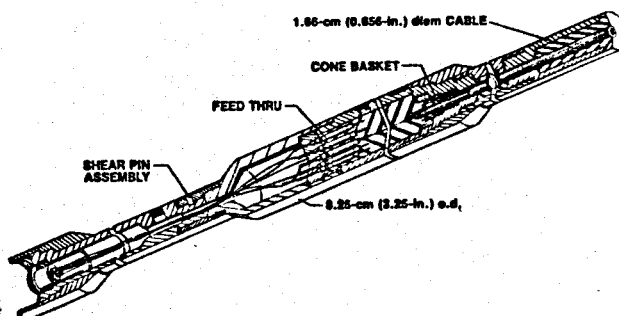


Fig. 6. High-temperature cable-head assembly.